S101 Unit 32

THE OPEN UNIVERSITY

Science: A Foundation Course

Science and the Planet Earth II: problems of survival

The Open University

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Unit 32
Science and the planet Earth II: problems of survival

Prepared by the Science Foundation Course Team

The Open University Press

SCIENCE

S101 Course Team List

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1 Introduction

If you think the title of this Unit would be more suitable for a whole Course than a single Course Unit, we agree with you. The problems that are likely to affect the chances of human survival on the planet Earth include those of population and poverty, food supply and disease, pollution and peace, physical resources and the preservation of the physical environment. Clearly, the study of such a broad range of complex problems is far beyond the scope of a single Course Unit, and we are not going to ask you to attempt it.

However, these global problems are so closely interconnected that it is impossible to go very far with studying any one of them without having to consider the others as well. So what we shall do in this Unit is to focus attention upon a single aspect of this set of problems. By studying one aspect in as much depth as is possible in the limited time available, we hope your interest in these problems will be aroused and that you will be more aware of how closely connected to each other they are. In a sense, then, you should see this Unit as an introduction, an invitation, to further study.

This Unit is also the concluding one of this Science Foundation Course, and that has influenced our choice of the particular aspect of the set of global problems that we are going to ask you to study. You have learned quite a bit about energy in this Course. Unit 8, in particular, was explicitly concerned with energy; but you have also seen, throughout the Course, many examples of physical, chemical, and geological processes that depend on the transfer or the transformation of energy. Such processes involve the motion of matter. To move anything that was not moving before, or to change the state of motion of anything, you have to apply a force to it and, in the process, transfer energy to it. So the conversion of energy from one form to another and its transfer from one object to another is fundamental to all material processes.

It is not surprising, therefore, that the question of how mankind is going to be able to meet its needs for energy in useful forms is one which penetrates many of the global problems we have mentioned. Take, for instance, the production, processing and distribution of food. At every stage in the process there are energy conversions or transfers, without which the process cannot take place.

So the approach to *problems of survival* that we have chosen for this Unit is to ask some questions about energy:

1 Does humanity *need* energy in certain useful forms, such as transportable fuels, or electricity, in order to escape from poverty, and if so, why? (Section 2)

2 Is it possible to make a realistic estimate of future *demand* for useful energy? (Section 2)

3 What are the actual and potential sources of energy from which it might be possible to meet such a demand? (Section 3)

4 What are the environmental hazards implicit in meeting such a demand from these sources? (Section 4)

5 Are the problems posed by questions 1 to 4 soluble in principle? And if they are, what are the technological, economic and political factors that are likely to determine whether the problems will be solved in practice? (Sections 5 and 6)

It must be emphasized that this Unit deals with questions about which there is much uncertainty and controversy. The science of climatology, for instance, is of central importance in our discussion, yet it is at such a rudimentary stage of development as to be unable to give clear, unequivocal answers to even the most obvious and seemingly simple questions, such as 'what will happen to the climate if the global average temperature increases by one or two degrees?'.

As a result, you can find that recognized experts express contradictory views in the books, articles and papers on the subject. We have had to make our own selection from these in order to give you a reasonably brief account of what seems to us to be the most important points. We have also drawn our own conclusions—which we offer to you for your critical examination. We are not

even unanimous within the S101 Course Team about all the views or judgements that are expressed in this text or about all the conclusions that are drawn. Indeed, one or two members of the Course Team expressed marked disagreement with a few of them. Obviously, you should feel free to do the same. However, we expect you will find, as the Course Team did, that in broad general terms the conclusions we have drawn from our analysis are not easy to refute.

Even the limited range of questions about energy that we have listed above cannot be answered in depth or in detail within the compass of a single Course Unit. We have had not only to be selective but also to exclude from the Main Text relevant data and technical detail, so that you can reasonably be expected to grasp the essential argument within the time you have available. This means that you will be asked to take our word for some conclusions that—given these data and the time—you could have worked out for yourself. It also means accepting, for the sake of argument, a number of assertions about the technical details of various processes, when—given the relevant information and the time to study it—you would be perfectly capable of judging whether these assertions are justifiable. So we have prepared a supplement to the Unit containing data, technical explanations and the like. We hope that when you are free of the stress of keeping up with the Course, you will use the information in this *Technical Supplement* to explore a little further some of the points you will have studied in the Unit itself.

We hope too that as a result of studying this Unit your interest in these problems will be aroused and your ability to approach them scientifically enhanced, and that you will want to do some further reading. So we have included a bibliography and some advice on further reading in Appendix 1.

2 Energy needs and demands

People need energy to grow and prepare food, to build, heat and light their houses, to keep industry working and transport on the move. In all these activities, the need for energy arises from the basic fact that, in one way or another, they all involve *moving things*, and that means transferring energy to them. The energy needed for such processes has to be available in a convenient form.

Throughout most of the history of human society, energy needs have been met very largely from immediately available, and essentially *renewable, energy sources* such as wood, wind and moving water. Since the Industrial Revolution, however, social production of goods, services and amenities has been based upon a very rapid growth in the demand for energy and, as you will see in Section 3.2, this demand has up to now been met almost entirely from *stored energy sources* in the form of fossil fuels (i.e. coal, oil and gas). The trouble is that fossil fuels are not renewable and so the world's limited energy capital is rapidly being depleted. Moreover, as you will see in Section 4.2, combustion of fossil fuels causes environmental problems that may prove so serious as to impose a limit more severe than that imposed by the exhaustion of recoverable resources. Another problem arises from the fact that, in all such energy conversion processes, some of the energy initially stored in the fuel is unavoidably wasted, that is, converted into a form that does not serve any useful purpose.

Consider the case of a coal-burning electrical power station. Once it is actually working, its output of electrical energy is usually less than 40 per cent of the heat energy produced by burning the coal in the furnaces—most of the rest is lost as waste heat. Even before getting to that stage, the station—and its associated power transmission system—had to be built and the coal had to be mined and transported to the station. All these processes need energy, and that energy comes almost entirely from fossil fuels. Thus, to make available a certain amount of *end-use energy* in some convenient form (such as electricity), a much larger amount of *primary energy*, initially stored in fossil fuels, has to be converted and in the process irretrievably used up. In practice, about three joules of primary energy are needed to provide one joule of electrical energy.

conversion efficiency

end-use energy

primary energy

There is a further gap between end-use energy and *functional energy*, which is the

functional energy

energy that serves a useful purpose. If you use the energy to heat your house, a significant proportion escapes through roof, walls and windows and heats up the neighbourhood instead of the inside of your house. So you can reduce the gap between end-use and functional energy by improving the thermal insulation of your house. Here is another example. When you buy petrol at a filling station, you are buying end-use energy in the form of a convenient fuel. To get crude oil out of the ground and convert it into petrol many processes are required, and these 'consume' primary energy. So only a fraction of the primary energy can be converted into end-use energy in the form of petrol. The *function* of this form of end-use energy is to make a machine work to transport you from one place to another. If you are stuck in a traffic jam in the rush hour, rather more end-use energy is needed to perform this function than would be the case if there were no traffic jam. So in this case, the gap between end-use and functional energy depends on such factors as town-planning, transport systems and social practices. And, of course, it depends on the efficiency of the vehicle you use.

It is important to distinguish between primary, end-use and functional energy, and to appreciate that the proportions of one to the other are not fixed and immutable. It is also important to distinguish between energy *demand* and energy *need*. Demand can to a considerable extent be conditioned by social custom and tradition, and by commercial pressures, such as advertising. It is even possible to meet a demand in such a way as to increase not only the demand but also the need. The classic example of this is the city in which the heat losses from air-conditioning plants increase the temperature outside enough to require still more air-conditioning plants to keep the buildings cool. Nobody would seriously suggest that the millions of North Americans who drive large uneconomic motor cars along overcrowded highways in and out of cities do so in order to improve the quality of their lives as compared, for example, with the Swiss or the Swedes.

This brings us to a final point that should be considered in this preliminary discussion of energy needs and demands. It is the question whether there is any correlation at all between end-use energy (let alone primary energy) conversion and 'quality of life'. Clearly, one's quality of life depends mainly on whether one has enough to eat, adequate clothing and housing, reasonable working conditions, adequate public and social amenities and services (like water, sanitation, medical and health services), cultural and educational provision, security in work and in old age, a healthy and pleasant environment, opportunities for leisure and recreation, and so on. But how do you measure these things?

It is very difficult to do this. It is, however, possible to measure, at least approximately, the level of *economic development* of a country (which should *not* be taken to mean the same thing as the 'standard of living' or 'quality of life' of its inhabitants) in terms of a quantity called the *Gross Domestic Product* (GDP). This may be defined as the money value of all goods and services produced in a country, excluding net income from abroad. The GDP is approximately equal to the sum of the wages, salaries and net profits received by the residents of the country.

Gross Domestic Product (GDP)

As a measure of relative economic development, GDP is a fairly reliable index for comparing industrially developed countries that have capitalist economies, but it is less reliable for comparing capitalist with socialist countries or industrially developed with industrially underdeveloped countries.

The standard of living of people clearly depends not only on the sum of wages, salaries and profits, but also on how these are distributed among the people. It is perfectly possible for a country to have a high per capita national income and for the great majority of its people to be extremely poor. There is, however, *some* correlation between GDP and primary energy conversion, in that very poor countries have very low levels of energy conversion and rich countries have high levels, but this does not show whether poor countries are poor because they do not have enough energy or whether these countries do not have enough energy because they are poor.

However, there are some fundamental reasons why countries with very low rates of per capita energy conversion are bound to be much poorer than countries with fairly high rates. Agricultural and industrial activities require energy to move things, and below a certain level of agricultural and industrial development a country will be poor, however equitable the distribution of such wealth as it has.

Data on population, GDP and rate of primary energy conversion for the year 1975 are given in Table 1. The rate of primary energy conversion is expressed as *power*. This is done by dividing the total energy converted in the year by the number of seconds in a year. This is then the power (or rate of energy conversion) averaged over the year.

TABLE 1 Population, power and GDP in 1975

	Population/10^6	Power/GW	GDP/G$
'Developed' countries (DC)	1 250	6 200	4 600
'Less developed' countries (LDC)	2 700	1 200	800
World	4 000	7 300	5 400

developed country (DC)

less developed country (LDC)

In Table 1, power is measured in GW (1 GW = 1 gigawatt = 10^9 W) and wealth, in terms of GDP, measured in G$ (1 G$ = 10^9 U.S. dollars). For the purposes of this Table, the 'less developed' countries are taken to comprise: Central and South America; Asia, excluding Japan; and Africa, excluding South Africa. You will find this Table in more detail in the *Technical Supplement*. The data in this Table are taken from the UN *Statistical Yearbook 1976*. Their reliability varies considerably between individual countries but, averaged over whole areas (as they have been in Table 1), they are probably correct to within 10 or 20 per cent. They have been rounded off accordingly.

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TABLE 2 Per capita GDP and power in 1975

	Power/kW	GDP/k$
DC	5.00	3.70
LDC	0.44	0.30
World	1.80	1.30

If you divide the figures in the GDP column of Table 1 by the figures in the power column, you get approximately the same ratio of 0.7 $/W for the DC, the LDC and the world as a whole. This indicates the rough correlation between GDP and power. However, a different point emerges if you divide the GDP and the power figures by the population figures (Table 2).

Thus, in 1975, the per capita power and GDP were more than ten times greater in the developed countries than in the less developed countries. Or, put another way, in 1975 the developed countries had 31 per cent of the world population but used 85 per cent of the primary energy (Figure 1).

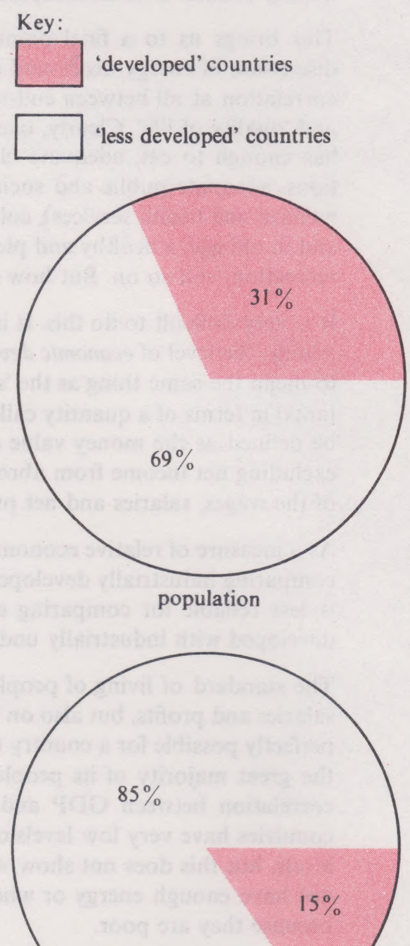

FIGURE 1 The division of population and of primary power or GDP between 'developed' and 'less developed' countries in 1975.

Is it possible to estimate the probable increase in world population into the next century and the likely energy demand of that population? It is important to make such predictions in order to ask where that much energy is to come from and what the environmental implications might be. One way of making such an estimate is to assume that current *rates of growth* of population and of per capita power remain essentially constant over a period. For instance, a projection by the UN Department of Economic and Social Affairs for the period 1975–2000 produced the figures given in Table 3.

TABLE 3 Estimated population and primary power in the year 2000 assuming that growth rates remain constant at approximately the 1975 levels

	Population/10^6	Power/GW	Per capita power/kW
DC	1 600	11 700	7.3
LDC	4 770	6 380	1.3
World	6 370	18 080	2.8

According to this projection, between the years 1975 and 2000, primary energy conversion would have risen by a factor of nearly 2.5, but per capita power in the developed countries in the year 2000 would still be more than five times greater than in the less developed countries.

In attempting to make estimates for the twenty-first century, it would *not* be realistic to assume that rates of growth of population and of per capita power will remain constant. In the developed countries, the population growth rate is decreasing and is expected to reach zero by the end of the century, after which the population would remain steady at about 1 500 million. In the less developed countries, the population is still increasing rapidly, but the growth rate may be expected to start falling off by the end of this century and to reach zero at some

time in the second half of next century. This would lead to a 'steady-state' population of around 9000 to 10000 million in those countries.

The population projections are illustrated in Figure 2, in which the area of each circle is proportional to the world population at the time. The Figure shows that the population in the at-present developed countries would drop from about a third to about an eighth of the world total.

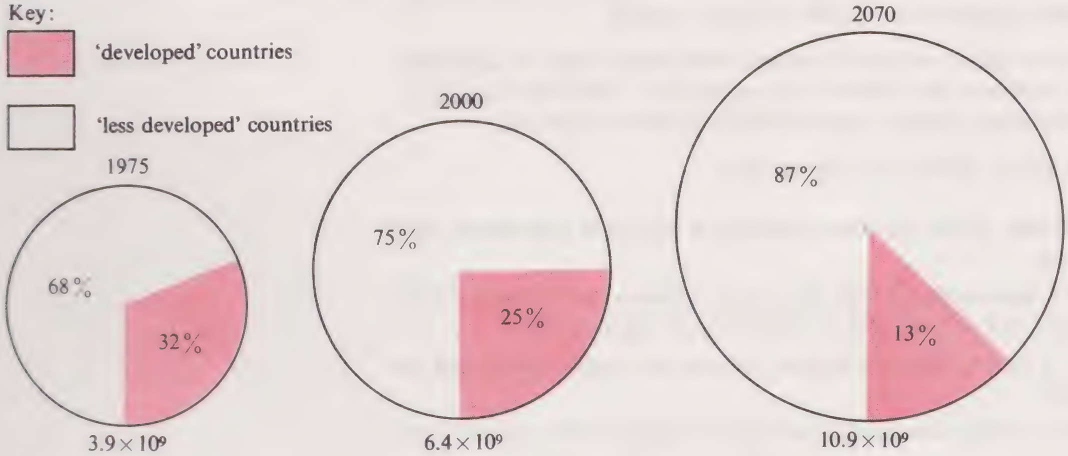

FIGURE 2 The division of population between the 'developed' countries (DC) and the 'less developed' countries (LDC) in 1975, 2000 and 2070. The projections assume that zero growth is achieved in the DCs by about 2010 and in the LDCs by about 2060. The areas of the circles are proportional to the total populations.

It is more difficult to estimate the future growth rate of the demand for primary energy. On the one hand, the gradual industrialization of those nations currently classified as LDCs will drastically increase the total energy requirement. The depletion of resources of itself increases energy requirements: primary energy sources will become more difficult to tap and such essential metals as copper and aluminium will become energetically more expensive to produce as stocks of their higher grade ores become exhausted. The technical and other measures being undertaken by governments in many of the highly industrialized nations to encourage economies in the use of primary fuels are not likely to go very far towards offsetting the *world* increase in the demand. It is only as the per capita consumption in the LDCs approaches that of the present DCs that it may be politically realistic to expect the growth rate of energy consumption to fall off, eventually to zero.

If one makes the *optimistic* assumption that zero growth in both population and per capita power can be achieved in all countries by about the year 2070, then it may be calculated that the annual demand for primary energy in the steady state will be about 70 TW*, or ten times the present level.

These energy projections are illustrated in Figure 3, in which the area of each circle is proportional to the estimated primary energy demand at the time. The

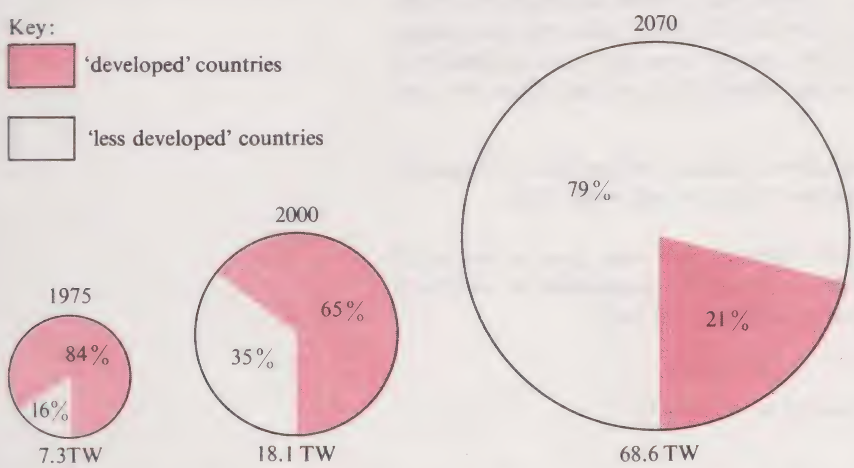

FIGURE 3 The division of primary power between the 'developed' countries (DC) and the 'less developed' countries (LDC) in 1975, 2000 and 2070. The projections assume (a) population growth as in Figure 2, (b) zero growth in per capita power is achieved in the DCs by about 2025 and in the LDCs by about 2060. The areas of the circles are proportional to the total primary power.

Figure shows that in 2070 about four-fifths of the primary energy demand would be in the *at-present* less developed countries, in which, as you saw from Figure 2, about seven-eighths of the world's population would be living. The calculations show that, on these assumptions, per capita power in the at-present developed

* 1 TW = 1 terrawatt = 10^3 GW = 10^{12} W.

countries would be between about one-and-a-half times and twice the per capita power in the *at-present* less developed countries**.

This is a good place to pause and look back over the ground we have covered so far. Try to jot down a set of notes summarizing the main points of this Section. Then compare your notes with ours, which are in the box on p. 12.

In Section 3, we shall consider what are the sources of energy from which it might be possible to meet a demand for 70 TW of primary energy.

You should now be able to explain in simple terms what degree of correlation there is between economic development (as measured by GDP) and rate of primary energy conversion, and why any correlation might be expected.

Here is an SAQ to test whether you can do this.

SAQ 1 Which of the following assertions is true or at least partly true? Give reasons.

A There is necessarily a rough correlation between the *standard of living* of the people of a country and the country's *per capita GDP*.

B There is no correlation whatever between per capita power and per capita GDP.

C There is a rough correlation between per capita GDP and per capita power.

D If country A has twice the per capita power of country B it will necessarily have twice the per capita GDP.

E In general, if the per capita power of a country differs by one or two orders of magnitude from that of another country, then the per capita GDP of the two countries will also differ by one or two orders of magnitude.

3 Energy sources

3.1 A review of energy sources

Energy sources may be divided into two major categories: energy capital and energy income.

3.1.1 Energy capital

energy capital

In this category we include the *fossil fuels* (coal, oil and natural gas), and the *nuclear fuels* (uranium and thorium).* If controlled nuclear fusion proves practicable, then deuterium may be added to the list of nuclear fuels, and also lithium (for reasons we shall explain below). We use the term *fuel* here to describe a material that is a source of *stored energy*, chemical or nuclear. These are *non-renewable* sources of energy.

By way of revision of what you learned about chemical fuels in Unit 15, Section 4, and about nuclear fuels in Unit 30, Section 7, try the following ITQs.

ITQ 1 In Section 5 of Unit 15 (Table 4) you were given a number of examples of exothermic reactions involving the combustion of fossil fuels such as carbon (in coal) and methane (in natural gas):

(1) $$C(s) + O_2(g) \longrightarrow CO_2(g);$$
$$\Delta H = -394\,\mathrm{kJ\,mol^{-1}} = -33\,\mathrm{MJ\,kg^{-1}}$$

** If you would like to check these calculations for yourself (we would suggest *after* you have completed the Course!), you will find the details in the *Technical Supplement*. Meanwhile, note simply from Figures 2 and 3 that the power/population ratios for 2070 are:

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LDC: $79\%/87\% = 0.91$; DC: $21\%/13\% = 1.6$. Ratio DC/LDC $= 1.6/0.91 \approx 1.8$.

* The use of thorium as a nuclear fuel instead of, or in addition to, uranium, has not yet (1979) received anything like the amount of attention that has been given to uranium. For this reason, we do not discuss thorium-based nuclear energy in this Unit.

(2) $$CH_4(g) + 2O_2(g) \longrightarrow CO_2(g) + 2H_2O(g)$$

$$\Delta H = -800\,\mathrm{kJ\,mol^{-1}} = -50\,\mathrm{MJ\,kg^{-1}}$$

And in Section 7 of Unit 30 we described two nuclear reactions in which energy is released—the fission of uranium and the fusion of deuterium:

(3) $${}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{95}_{39}\mathrm{Y} + {}^{139}_{53}\mathrm{I} + 2{}^{1}_{0}\mathrm{n} + 200\,\mathrm{MeV}$$

(4) $${}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \longrightarrow {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + 3.4\,\mathrm{MeV}$$

(a) Can you explain in a few sentences why the chemical reactions (1) and (2) are exothermic and why the nuclear reactions (3) and (4) also release energy?

(b) Given that $1\,\mathrm{MeV} \approx 1.6 \times 10^{-13}\,\mathrm{J}$ and that there are $\sim 6 \times 10^{23}$ atoms in 235 g of ${}^{235}_{42}\mathrm{U}$ or in 2 g of ${}^{2}_{1}\mathrm{H}$, calculate the energy release per gram of nuclear fuel in reactions (3) and (4) and compare this with the energy release per gram of chemical fuel in reactions (1) and (2). How do you explain the difference?

ITQ 2 The term 'stored energy' suggests some process whereby the energy (perhaps originally in some other form) got 'stored', for instance, in the reactant molecules of reaction (1) in ITQ 1, carbon and oxygen. Can you recall from earlier Course Units what these processes were, and where the 'stored energy' came from?

The energy 'stored' in fossil fuels like coal, oil or natural gas is in a certain sense 'stored solar energy'. Fossil fuels and nuclear fuels are described as non-renewable fuels. Why are they not renewable?

Coal was formed in the Carboniferous over a period of about 10^8 years. This is a very long time compared with the time in which most of the recoverable coal is likely to be used up—which, as you will see below, is a matter of only a few centuries. So, even if the conditions of the Carboniferous *were* to be reproduced at some time in the Earth's future history, for all the practical purposes that concern mankind (and us in this Course Unit) that would hardly make coal a renewable resource! Similarly, the formation of petroleum is such a very slow process (though it is going on now in places like the Black Sea) that the exhaustion within the next century of the recoverable petroleum formed over the past few hundred million years puts it too in the category of a non-renewable fuel.

The same argument applies to nuclear fuels, only more so. Atoms of uranium and thorium are not now being created in the Earth at all.

3.1.2 Energy income

energy income

In this category we include all essentially renewable sources of energy. Of these, by far the largest is *solar energy*. The quantity of solar energy reaching the Earth's surface in a year is truly enormous: approximately 2×10^{24} J, which is nearly seven thousand times the total primary energy conversion from fossil fuels in the year 1975.

biosphere

Solar energy is an input to the biosphere (the thin layer near the Earth's surface inhabited by living matter) that is continually available (within the Sun's lifetime), whether we convert it temporarily into other forms of energy or simply let it be transferred directly to the system as heat. Sunlight can be transformed directly into *end-use energy* in a variety of ways. It can be used to heat water that is to be used as such. Or it can be used to heat water (or oil or salt) in a storage device, and the heat transferred over a longer period of time to the air inside a building—this is called 'space-heating'. Alternatively, it can be used to generate electricity in devices such as photoelectric cells. In this case, the end-use energy is electrical, and the functional energy may, for instance, be the kinetic energy of, say, an electric train.

There are many ways in which solar energy may be converted *indirectly* into end-use energy. Solar energy could be used instead of chemical energy from coal, for instance, to generate steam and hence electricity in a power station. Or it may be converted into chemical energy in the form of a transportable fuel such as hydrogen or methanol. A still more indirect conversion of solar energy would be to convert it first into chemical energy by photosynthesis of organic matter, and then use the organic matter as a fuel. This could be done directly, by burning the

Summary notes for Section 2

1 What do people need energy for? Essentially, to *move* things.

2 Distinguish between *need* and *demand*. Demand can be conditioned by social custom and tradition, and by commercial pressure.

3 Distinguish between *primary*, *end-use* and *functional energy*.

4 Correlation between *end-use energy* and:

(a) '*quality of life*' or '*standard of living*'?

(b) *economic development* as indicated (crudely) by *GDP*?

Can't answer (a)—lack of any acceptable way of measuring 'quality of life' or 'standard of living'. (Wrong to equate standard of living of people with per capita GDP of the country they live in.) There is a crude correlation between per capita GDP and per capita power (or energy)—poorer countries have much less of both than the richer ones do. But this correlation does not in itself establish a causal relationship. Nevertheless, because all industrial and agricultural activities require energy—essentially for moving things—there are fundamental reasons for expecting that countries with very low per capita power are likely to be poor. This—set against the hard fact that, in the mid-1970s, the countries inhabited by about a third of the world's population had 85 per cent of both wealth and the power—provides grounds for expecting that there will be political pressure from the poorer countries to reduce the 'power gap'.

5 Noted present trends in population and in per capita power, and the 'steady-state' population and power levels that would be reached on certain 'optimistic' assumptions about growth rates. (It must be emphasized that these were *assumptions*.) Since, however, these assumptions took some account of present growth rates and of the factors that are likely to determine how quickly these growth rates can be reduced to zero, the conclusions based on them should, for the time being, be regarded as at least plausible. If anything, they are perhaps rather optimistic about the possibilities of achieving zero growth in both population and per capita power by about the middle of next century.

6 On these assumptions, in the steady state the annual world demand for primary energy may reach the equivalent of about 70 TW (or even more?).

organic matter itself (e.g. wood), or it could be done indirectly, by producing fuels such as hydrogen or methane or methanol from the organic matter. In the process of producing the synthetic fuel, more solar energy might be converted into chemical energy.

We shall describe these energy conversion processes further in Section 3.3, and you will find more details in the *Technical Supplement*. **TS**

A more familiar example of indirect conversion of solar energy is *hydroelectrical energy*. Do you remember the visit we made to Cwm Dyli power station, in the TV programme associated with Unit 8? There, gravitational energy was being converted into electrical energy and heat. It was solar energy, however, that originally evaporated water from the ocean surface which in turn condensed into clouds and fell as rain on the mountainside and thence accumulated in the reservoir. Thus solar energy was first converted into gravitational energy and then into electrical and heat energy.

Since you have just been thinking about rain, what about wind and waves? If you generate electricity from the motion of the air past a windmill, or from the motion of the waves past some device capable of turning the wave motion into rotatory motion, what is the original source of the energy you are thus converting? Again, it is solar energy, for that is what drives the atmospheric air currents (winds) and hence the waves.

While you are thinking about the oceans, there is yet another source of indirect solar energy that, as you will see, may prove to be one of the most important ones. The solar radiation incident upon the ocean surface warms up the upper layers, especially in the tropical latitudes. The deeper water remains cold. There may be a temperature difference of as much as 20 °C between the two. It is possible in

principle (and may prove practicable) to use the heat energy stored in the warm upper layers to boil a liquid like ammonia or freon, use the high-pressure vapour to drive a turbine and generate electricity, and condense the vapour back to liquid by cooling it with cold water from the deep layers. Such a system could be called an *ocean thermal energy* system. You will find a more detailed description of it in Section 3.3.2.

The two other sources of energy we should mention to complete our list are *tidal energy* and *geothermal energy*.

Given the right geographic and topographic conditions, the gravitational energy stored in water masses at high tide can be used to generate electricity in much the same way as in a hydroelectric power station. But where does that gravitational energy come from? What forces are responsible for the tidal motions of the water on the Earth's surface?

The gravitational force of the Moon and the Sun on the oceans and the rotational motion of the Earth are together responsible for the tides. So the origin of tidal energy must be in the kinetic and gravitational potential energy of the Sun–Moon–Earth system. Eventually, the kinetic energy of tidal motion is converted into heat energy through friction. There is a corresponding loss of energy from the Sun–Moon–Earth system, which minutely affects their orbital motion and the spin of the Earth. (We mentioned in Unit 2 that this causes the mean solar day to get longer by about 1.5×10^{-5} seconds each year.) For all practical purposes, tidal energy is renewable; it comes from such an enormous 'store' of capital energy that it can be regarded as energy income, which we receive anyway, whether we use it or not.

Can you recall what is the source of geothermal energy—the heat flowing out of the Earth's interior?

Its origin is the radioactive decay of elements like uranium and potassium, and these are not a renewable resource. In this sense, geothermal energy may be regarded as 'capital' rather than 'income'. But again, as in the case of tidal energy, the amount of energy stored 'in the bank' is so large compared with the rate of withdrawal from it that, over the time-scale of interest to us, it may be regarded as renewable energy, or energy income.

The energy sources we have reviewed in this brief preliminary survey are listed in Table 4, in which the right-hand columns have been left blank so that you can write your own notes there (we suggest that you do this in pencil, as you may change your mind as you progress through this Unit!). You might, for instance, wish to note whether the source listed in the first column is, or may in future be, a large-scale energy source, capable of meeting an appreciable fraction of the primary energy demand (say 10 per cent or more). You might wish to note in the other columns your own judgements about whether the technology concerned is well known or uncertain, whether there are environmental hazards, and so on.

Table 4 is on p. 14.

The questions we want you to think about next are:

1 Which, if any, of the energy sources listed in Table 4 are capable of meeting the sort of energy demands (equivalent to a continuous primary power of about 70 TW) anticipated in Section 2, Figure 3?

2 What are the environmental implications of meeting such a demand—or a significant proportion of it—from any, some or all of these sources?

But first, you should check whether you have achieved the main Objective of Section 3.1, which is that you should be able to explain in simple terms (or distinguish between correct and incorrect explanations of) what is meant by: energy capital, energy income, non-renewable energy, renewable energy, fuel, stored energy, and to give appropriate examples.

Here is an SAQ to test this Objective.

SAQ 2 Each question in this SAQ consists of a statement followed by a key A–G. You are asked to decide whether the statement is true or false (item A or B) and then select up to two of the items in C to G that in your view most strongly support your decision about the statement.

TABLE 4 A list of energy sources

Form of energy	Actual or potential scale	Advantages	Disadvantages
CAPITAL			
Fossil fuels			
coal			
oil			
natural gas			
Nuclear fuels			
uranium/thorium			
deuterium			
(lithium)			
INCOME			
Direct solar energy			
water/space heating			
photoelectricity			
Indirect solar energy			
thermo-electrical			
hydrogen generation			
photosynthesis: wood, synthetic fuels			
hydroelectrical			
wind			
wave			
ocean thermal			
Tidal energy			
Geothermal energy			

(a) As you may know, wood is an important source of energy in the less developed countries.

Statement For sufficiently low rates of usage, wood is an example of energy income.

A The statement is true.

B The statement is false.

C There is stored chemical energy in wood.

D Wood is a fuel, and all fuels are examples of energy capital.

E On the time-scales to which our working definitions of energy capital and energy income apply, wood is a renewable energy source.

F Once burned, wood cannot be replaced.

G Wood is a form of solar energy, stored as chemical energy by photosynthesis.

(b) *Statement* Geothermal energy is an example of energy capital.

A The statement is true.

B The statement is false.

C The origin of geothermal energy is the friction of crustal plates in subduction zones.

D Geothermal energy, like solar energy, reaches the Earth's surface and heats it up, whether we use it temporarily for something else or not.

E The origin of geothermal energy is the decay of radioactive elements in the Earth's interior.

F Geothermal energy is a non-renewable form of energy.

G On the time-scales to which our definition of energy income and capital apply, the flow of geothermal energy to the Earth's surface will remain essentially constant.

3.2 Energy capital sources

3.2.1 The present pattern of energy conversion

As you can see from the data in Table 5, in the mid-1970s, practically all primary energy came from the combustion of fossil fuels.

TABLE 5 Primary energy conversion in 1975*

	Equivalent constant power/GW	Percentages of power from each source			
		coal	oil	natural gas	hydro- and nuclear-electric**
Developed countries	6059	29.6	44.7	22.9	2.8
Less developed countries	1287	47.7	40.9	8.8	2.6
World	7346	32.8	44.0	20.4	2.8

* UN statistics, published in 1977.

** 'Nuclear-electric' means electrical energy generated in power stations using nuclear fuel.

ITQ 3 According to the estimates illustrated in Figure 3 (p. 9), primary power demand would increase from 7.3 TW in 1975 to 18.1 TW in 2000. If this increase were to be met entirely from nuclear sources, how many nuclear power stations would need to be built *per day* between 1975 and 2000 if each nuclear power station converted nuclear energy into electrical energy and waste heat at an average rate of 1 GW?

Few knowledgeable people would say that such a rapid growth of nuclear power as the answer to ITQ 3 reveals is possible and, as you will see, there are reasons why it may not be desirable even if it is possible. Energy income sources are unlikely to be developed quickly enough and on a large enough scale to add as much as 10.8 TW to primary energy in the 25 years from 1975 to 2000. The reasons for this will become clearer when you have read Section 3.3. So it looks as if, by the turn of the century and perhaps for quite some time after that, we may still be relying very heavily upon fossil fuels to meet global energy demands. How long will these fossil fuels last?

3.2.2 Estimated reserves of fossil fuels

Coal

Reasonably good estimates of the amount of coal deposits in a given region can be made by geological mapping combined with suitably spaced drill holes, since coal is found in stratified beds or seams that usually extend over considerable areas.

On the basis of such studies, which have been made all over the world, fairly reliable estimates have been made.

A recent estimate of recoverable coal reserves made by the U.S. Geological Survey put the world total at around 8×10^{12} metric tonnes*. (But note that experts can disagree by a factor of two or three about how much of this can be usefully *worked*.)

According to the estimate illustrated in Figure 3 (p. 9), primary power demand might increase to a steady-state level of about 70 TW. If *all* this had to come from coal, how long would the coal reserves last? To answer this question we need to know how much energy may be obtained from a tonne of coal. This depends on the quality of the coal. If we use the generally accepted average figure of 0.93 kW yr per tonne**, then 8×10^{12} tonnes will yield:

$$8 \times 10^{12} \times 0.93 = 7.44 \times 10^{12}\,\text{kW yr}$$
$$= 7.44 \times 10^{3}\,\text{TW yr}$$

So, at the rate of 70 TW, that amount of coal would last $7\,440/70 \approx 106$ years.

Oil

Estimating the amount of oil (and natural gas) reserves is rather more difficult than estimating coal reserves, because oil deposits are located in restricted volumes and limited areas in sedimentary basins at depths ranging from a few hundred metres to more than eight thousand metres. Nevertheless, the conditions necessary for the occurrence of oil and the location of the main sedimentary basins are sufficiently well known for it to be possible to make approximate estimates of total recoverable reserves.

Estimates of world petroleum reserves made in 1974† put the 'initially recoverable reserves' (i.e. recoverable with presently available technology) at around 590 TW yr, including the contributions of tar sands (75 TW yr), shale (59 TW yr) and natural gas liquids, such as propane and butane, associated with petroleum deposits (56 TW yr). The main contribution of 400 TW yr is from crude oil.

A more recent estimate†† of world *proved* reserves of crude oil was quite a bit lower: 130 TW yr. By *proved* reserves is meant definitely located and known to be recoverable at today's prices and with today's technology.

Another recent estimate‡, this time of total world reserves, both discovered and undiscovered (but thought to be probably discoverable), sets an upper limit of about 1 000 TW yr.

Whichever one of these estimates you take, it represents only a small percentage of the estimated coal reserves of 7 400 TW yr.

Natural gas

Until quite recently, natural gas was regarded as a waste product of oil production, and if it could not be used on site it was burned off. With developments in transportation by pipelines and refrigerated tankers, natural gas is now making a significant contribution to world energy needs (about 20 per cent in 1975, see Table 5).

Natural gas is usually associated with oil, but there are important sources of natural gas produced by the gasification of coal. Unlike coal or oil, natural gas is an extremely clean and convenient fuel. Unfortunately, reserves of natural gas are estimated to be somewhat less than reserves of petroleum, perhaps 400 TW yr.

* 1 metric tonne = 10^3 kg.

** As you can verify for yourself, this corresponds to 2.93×10^{10} joules per metric tonne.

† From a report to the U.S. Congress by M. K. Hubbert.

†† From the *Oil and Gas Journal*, cited in a Barclays Bank Commodity Report in March 1978.

‡ By an energy expert of the World Bank, quoted by the *Financial Times* in May 1978.

Fossil fuels—summary

The estimated global reserves of fossil fuels are thus:

coal	~	7 400 TW yr
oil	~	say, 400 TW yr
gas	~	400 TW yr
total	~	8 200 TW yr

If primary energy demand grows as projected in Figure 3, and if all or almost all of it is to come from fossil fuels, it is clear that they are most unlikely to last for more than a century or so. When the fossil fuel epoch is viewed over a longer period of human history, it will be seen to have been but transitory.

Seen in this historical perspective, the present overwhelming dependence on fossil fuels (Table 5)—and the extent to which people have become accustomed to a pattern of energy conversion from fossil fuels that depends on its exponential growth—gives grounds for serious disquiet.

Moreover, we have said nothing of the fact that these same fossil fuels are also invaluable and irreplaceable raw materials, from which many important commodities (such as fabrics, structural materials and pharmaceutical products) are made. In addition, as you will see in Section 4, the combustion of fossil fuels has environmental effects that may prove to be a more serious limit than the exhaustion of recoverable reserves.

It is obvious from all this that, if anything like the energy demand projected in Figure 3 is to be met, some other major source of energy will have to be tapped. In the view of many dedicated technologists and, indeed, of many national governments, that source is most likely to be nuclear energy.

nuclear fuel

3.2.3 Nuclear fuels

To understand the possibilities and problems of nuclear energy, you need to be aware of the essential working principles of nuclear reactors, so here is a brief explanation of them. You will find further details in the *Technical Supplement*.

TS

You saw in Unit 30 that energy may be obtained from nuclear reactions of the type:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \longrightarrow ^{236}_{92}\mathrm{U} \longrightarrow ^{95}_{39}\mathrm{Y} + ^{139}_{53}\mathrm{I} + 2^{1}_{0}\mathrm{n} + 200\,\mathrm{MeV}$$

in which the $^{235}_{92}\mathrm{U}$ nucleus captures a neutron and the highly unstable $^{236}_{92}\mathrm{U}$ nucleus undergoes *fission*, producing two fission-product nuclei of intermediate mass (in this example $^{95}_{39}\mathrm{Y}$ and $^{139}_{53}\mathrm{I}$), two neutrons and energy—most of it in the form of kinetic energy of the fission fragments and neutrons.

The chance of a $^{235}_{92}\mathrm{U}$ nucleus capturing a neutron and undergoing fission is much greater if the neutrons are moving very slowly. So a material, such as carbon, which slows down the fast neutrons emitted from the fission reactions, is incorporated in the reactor. This material is called the *moderator*.

moderator

Naturally occurring uranium contains only 0.7 per cent $^{235}_{92}\mathrm{U}$, the rest being $^{238}_{92}\mathrm{U}$. The latter does not undergo fission, but absorbs neutrons and is transformed into another material, plutonium, $^{239}_{92}\mathrm{Pu}$*, which is fissionable.

This process, in which non-fissionable material is transformed into fissionable material, is called *breeding*. It occurs in *all* nuclear fission reactors. Some of the $^{239}_{94}\mathrm{Pu}$ undergoes fission, just like $^{235}_{92}\mathrm{U}$, releasing energy and neutrons in the process. Some of the $^{239}_{94}\mathrm{Pu}$ captures neutrons and, instead of undergoing fission, gets transformed into $^{240}_{94}\mathrm{Pu}$, which is not a fissionable material.

breeding (of fissile fuel)

* This takes place in three steps:

1 $^{238}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \longrightarrow ^{239}_{92}\mathrm{U}$

2 $^{239}_{92}\mathrm{U} \longrightarrow ^{239}_{93}\mathrm{Np} + e^- + \nu$ (β^--decay)

3 $^{239}_{93}\mathrm{Np} \longrightarrow ^{239}_{94}\mathrm{Pu} + e^- + \nu$ (β^--decay)

Figure 4 illustrates the three processes we have described. In (a), a $^{235}_{92}U$ nucleus captures a neutron and undergoes fission, in which three neutrons are produced. In (b), a $^{238}_{92}U$ nucleus captures a neutron and is transformed by β^--decay into $^{239}_{94}Pu$, which captures a neutron and undergoes fission, in which two neutrons are produced. In (c), a $^{238}_{92}U$ nucleus captures a neutron and is transformed by β^--decay into $^{239}_{94}Pu$, which captures a neutron and is transformed into $^{240}_{94}Pu$. This isotope of plutonium, which accumulates comparatively rapidly, can undergo spontaneous fission, but is unlikely to do so when struck by a neutron, and cannot therefore participate in a chain reaction. Uranium fuel elements taken out of a reactor will contain a mixture of $^{240}_{94}Pu$ and $^{239}_{94}Pu$, as well as a variety of extremely radioactive *fission products*.

fission product

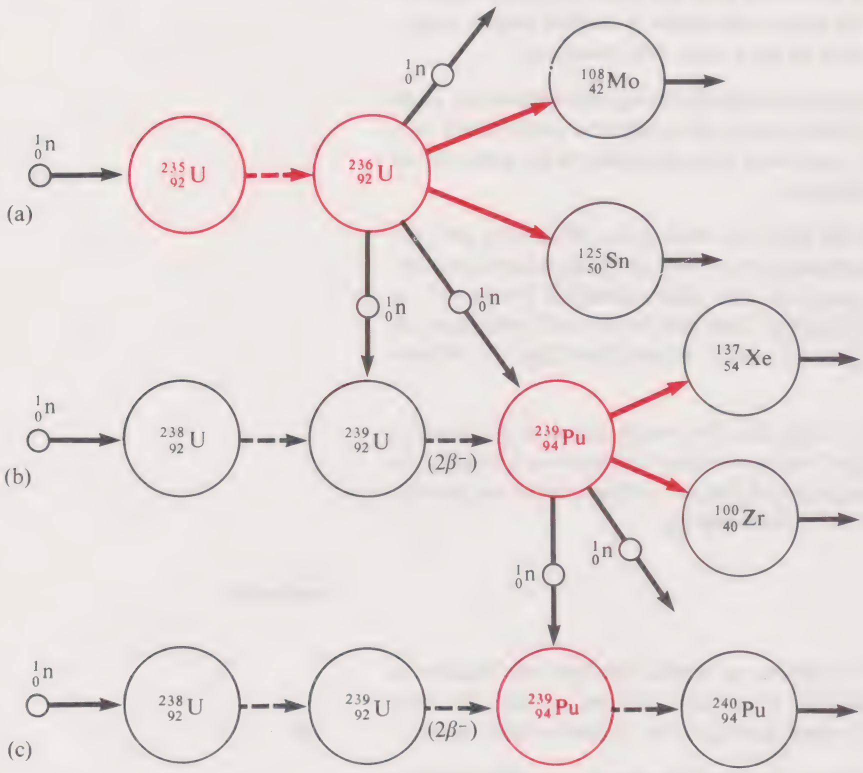

FIGURE 4 Neutron capture and fission processes in a nuclear reactor.

(a) A $^{235}_{92}U$ nucleus captures a neutron and undergoes fission.

(b) A $^{238}_{92}U$ nucleus captures a neutron and decays to $^{239}_{94}Pu$, which then captures a neutron and undergoes fission.

(c) A $^{238}_{92}U$ nucleus captures a neutron and decays to $^{239}_{94}Pu$, which then captures a neutron and is transformed into $^{240}_{94}Pu$.

There is just one more principle of nuclear reactors that you need to know about in order to appreciate the possibilities of nuclear energy. This is the distinction between the type of reactor we have been describing and a different type known as the *fast breeder reactor* (FBR). The basic principle of all reactors, other than the FBR, is fission of $^{235}_{92}U$ or of $^{239}_{94}Pu$ by *slow* neutrons. These slow neutrons are sometimes called 'thermal' neutrons, and reactors based on fission by slow neutrons are consequently known as *thermal reactors*. Even in a thermal reactor, some of the neutrons are absorbed by $^{238}_{92}U$ and produce $^{239}_{94}Pu$, which may then undergo fission and add appreciably to the total release of energy. But the amount of plutonium created is less than the amount of uranium used up, so such reactors are also called *burner reactors*. In this context, the $^{238}_{92}U$ may be called *fertile material*—it can be used to 'breed' new *fissile material*. In a reactor containing both fertile and fissile material, the ratio (fertile nuclei converted to fissile nuclei)/(fissile nuclei consumed) is called the *conversion ratio*. In a *burner reactor* the conversion ratio is less than 1. In a *breeder reactor*, it is greater than 1—the reactor produces more fissile material than it consumes. To breed new fissile material in a chain reaction, at least two neutrons are required from each fission: one to carry on the reaction by causing a further fission, and one to convert a fertile nucleus into a fissile one. In practice some neutrons are captured by coolant and structural materials in the reactor, so one needs appreciably more than two neutrons per fission. This is best achieved by the fission of $^{239}_{94}Pu$ by *fast neutrons*. Fission of $^{235}_{92}U$ by fast neutrons will work, but is less efficient.

fast breeder reactor (FBR)

thermal reactor

burner reactor **fertile material**

fissile material

conversion ratio

breeder reactor

fast neutrons

A reactor that produces more fissile material than it consumes, by using a reaction dependent on fast neutrons, is called a *fast breeder reactor*. Only a few FBRs have been constructed and their further development is subject to many uncertainties. These stem essentially from the fact that it takes about 400 times as many fast neutrons as thermal neutrons to cause a fission. Consequently, a much higher neutron density must be created, and the emergent neutrons must not make collisions that would slow them down before they strike other fertile nuclei. So the core of a FBR must be much more compact than that of any thermal reactor, it must contain no moderator, a minimum amount of other structural material and only so much coolant as will suffice to carry away the intense heat produced in the core. The technological problems of designing such reactors and operating them successfully are very complex.

Now that you have the essential distinction between a 'burner' and a 'breeder' reactor in mind, you are in a position to judge whether estimated global resources of uranium are large enough for nuclear fuels to be able to take over from fossil fuels, given the following information.

Uranium resources

Uranium is normally found in the form of a mixture of oxides, ranging from UO_2 to U_3O_8. Uranium resources are accordingly specified, as a rule, in tonnes of U_3O_8. Since the cost of mining and processing the uranium ore depends on its 'grade' (i.e. the concentration of uranium oxide in it), estimates of resources are always related to the cost (in terms of money, not energy) of extraction of the U_3O_8. High-grade uranium ores contain up to 4 per cent uranium, but known reserves of this quality have been largely used up, and ores of ten times lower uranium content, 0.4 per cent or less, are now being worked. Ores of about this quality could, in the mid-1970s, be processed at a cost that made the generation of electricity from nuclear fuels economically viable by comparison with fossil fuels. Global resources of uranium ores of that quality were then estimated at about three to four million tonnes of U_3O_8*. Since the price of fossil fuels is likely to increase sharply in the future, lower-grade uranium ores may well prove economically viable.

On this basis, global resources of uranium might be estimated, very roughly, to be in the region of 10 million to 20 million tonnes of U_3O_8.

> How much energy can be obtained from 10^7 tonnes of U_3O_8?
>
> You know that 0.7 per cent of the uranium in U_3O_8 is the fissile isotope ${}^{235}_{92}U$. You also know that the energy released per ${}^{235}_{92}U$ nucleus is 200 MeV, and that $1\ \text{MeV} = 1.6 \times 10^{-13}\ \text{J}$.
>
> From this we calculate that the energy obtainable from 10^7 tonnes of U_3O_8 is 4.9×10^{21} J or about 156 TW yr*.

If primary energy demand is to rise from about 7 TW in 1975 to about 70 TW in 2075, we may take a rough average for this century as about 40 TW. At this rate, 10^7 tonnes of U_3O_8 would last barely four years! Even if nuclear fission of ${}^{235}_{92}U$ had to supply, say, only ten per cent of the total, the estimated global resources of uranium would last only 40–80 years.

It is obvious from this simple calculation that fission of uranium in burner reactors, which have conversion ratios less than one, will not meet the world power demand anticipated in Figure 3. This is why there is so much interest in the possibilities of breeder reactors.

* *World Energy Conference Survey of Energy Resources, 1974*, UN, New York.

** The calculation is straightforward. In answering ITQ 1(b), you have already calculated the energy released per gram of ${}^{235}_{92}U$; it is 8.2×10^{10} J.

The mass of uranium in 1 tonne of U_3O_8 is: $[(3 \times 238)/(3 \times 238 + 8 \times 16)] \times 1\ \text{tonne} \approx 0.85$ tonnes.

So the mass of ${}^{235}_{92}U$ in 10^7 tonnes of U_3O_8 is: $0.85 \times 0.007 \times 10^7\ \text{tonnes} \approx 6 \times 10^4$ tonnes.

Hence the energy released from 10^7 tonnes of U_3O_8 is:

$$6 \times 10^4 \times 10^6 \times 8.2 \times 10^{10}\ \text{J} \approx 4.9 \times 10^{21}\ \text{J}.$$

Hence the energy released from 10^7 tonnes of U_3O_8 is: $6 \times 10^4 \times 10^6 \times 8.2 \times 10^{10}\ \text{J} \approx 4.9 \times 10^{21}\ \text{J}$.

This may be converted into units of terawatt years (TW yr), using the relation: $1\ \text{TW yr} = 10^{12}\ \text{W yr} = 10^{12} \times 365 \times 24 \times 3\,600\ \text{W s} = 3.15 \times 10^{19}\ \text{J}$.

Thus, $4.9 \times 10^{21}\ \text{J} = (4.9 \times 10^{21}/3.15 \times 10^{19})\ \text{TW yr} = 156\ \text{TW yr}$.

For technical reasons that we do not have time to go into here, there is a limit to the rate at which fast breeder reactors can be expected to breed new fissile material. Taking this limit into account, it is customary to estimate the effective energy content of a given mass of uranium as being a factor of 60 times greater if the uranium is used in breeder reactors than if it is used in burner reactors.

Thus, 10^7 tonnes of U_3O_8 would have an effective energy content of $60 \times 156\,\text{TW yr} = 9\,360\,\text{TW}$. But, even with this 60-fold enhancement, that amount of U_3O_8 could meet fully a demand of 70 TW for only about 130 years.

It seems then that uranium cannot be seen as a replacement for fossil fuels, unless breeder reactors can be developed very quickly and on a large scale, and even then uranium will not be an unlimited resource.

In considering uranium reserves in terms of their *monetary* cost only, we have so far overlooked a factor that will certainly limit the rate at which nuclear power stations can be built and put into operation, whether they use burner or breeder reactors. This is the *energy cost* of building them and supplying the fuel for them. (You may remember the example of 'energy accounting' in Radio 04.)

If the energy 'consumed' in building and fuelling nuclear power stations exceeds for some years the energy 'produced' by them (which it will do if one tries to build them too quickly), then during that time the nuclear power programme represents a net *drain* on existing sources of energy. As you have seen, these are practically entirely fossil fuels. Since fossil fuels are now being depleted with alarming rapidity, the prospects of nuclear energy being developed rapidly enough to 'close the fuel gap' do not seem very bright. As you will see in Section 4.3, the serious environmental hazards of a large-scale nuclear power programme are likely to impose further restraints on it*.

The prospects of nuclear energy from *fission* thus seem to be rather limited. Will nuclear energy from *fusion* be the answer?

Fusion fuels

In Unit 30 we mentioned briefly an alternative exothermic nuclear reaction, that of fusion of heavy hydrogen isotopes, and we gave as an example the reaction:

$$^{2}_{1}H + ^{2}_{1}H \longrightarrow ^{3}_{2}He + ^{1}_{0}n + 3.4\,\text{MeV} \qquad (1)$$

Another example of such a fusion reaction is

$$^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6\,\text{MeV} \qquad (2)$$

The latter reaction involves the heaviest hydrogen isotope *tritium* ($^{3}_{1}H$), which does not exist in nature, is radioactive and decays by β^--emission with a half-life of 12.3 years.

To bring about the fusion of two heavy hydrogen nuclei, they have to be brought close enough together to allow the strong force to overcome the force of electrostatic repulsion. (Remember that the hydrogen nucleus contains one proton and thus carries a positive electrical charge.) This can be achieved by giving the hydrogen nuclei such large kinetic energies that they can get close enough in collisions with one another to be captured by the strong force before they have been stopped and repelled by the electrostatic force.

To give the hydrogen nuclei sufficiently large kinetic energies, the hydrogen has to be heated to a high temperature. Calculations and experiments have shown that for reaction (1) temperatures in the region of 10^7–10^8 °C are needed. Reaction (2) works at temperatures about 10 times lower, 10^6–10^7 °C. Such temperatures are found in the interior of stars, like the Sun. They are also produced in fission bombs. If a fission bomb is surrounded by material containing deuterium ($^{2}_{1}H$) or tritium ($^{3}_{1}H$) a 'hydrogen bomb' is produced. Another way of reaching such temperatures is by producing a powerful electrical discharge in hydrogen gas, or by using pulses of very intense light focused upon a small pellet of solid deuterium or tritium.

The problem that immediately arises is how to keep heat losses to surrounding materials, such as the structural materials of the reactor vessel, low enough to allow the deuterium or tritium to reach the required temperature and, indeed, to

* Of course, similar limits apply to the rate of growth of *any* new energy conversion technology that consumes a lot of energy in the construction stage.

avoid simply melting the containment vessel in the process. It is with alternative solutions to these problems that the 'controlled fusion' research of the last 30 years has been concerned, so far without much success. It is likely, though not certain, that at least one of several promising approaches will succeed within the next decade or so. This could lead to a large-scale prototype fusion reactor around the last decade of this century. It is likely to be extremely expensive, probably of the order of several hundred million pounds, and to incorporate a great deal of very advanced technology. The further development of fusion power would then be subject to the same technological and financial constraints as have limited the contribution of fission power to about one per cent of the power obtained from fossil fuel after thirty years of intensive research and development. Nevertheless, for reasons we shall discuss in Section 4.3, fusion power, if it proves to be feasible, would in the medium term be a preferable option to fission power as a temporary replacement for fossil fuels. What, then, are the resource limitations, if any?

If the deuterium–deuterium fusion reaction (equation 1) can be achieved in a large-scale reactor, the fuel supply would consist only of deuterium. So how much deuterium is available?

This is easily calculated, from the approximately known amount of water in the world's oceans ($\sim 1.4 \times 10^8$ tonnes), and the known proportion of deuterium in natural hydrogen (0.015 per cent). If you are interested, you can check this calculation for yourself. (You will find details in the *Technical Supplement*.) We find that even as tiny a fraction as 0.001 per cent of the deuterium in the world's oceans could produce about 6×10^5 TW yr of energy. At 60 TW, that would last 10 000 years.

Unfortunately, the deuterium–deuterium reaction requires much higher temperatures than the deuterium–tritium reaction and may prove to be technologically impracticable. In that case, what hope is there for fusion power, since tritium does not exist in nature in any significant quantities? There is, however, a way around this difficulty, which takes advantage of the fact that if one of the isotopes of lithium, ${}^6_3\mathrm{Li}$, is bombarded with neutrons, it is transformed into tritium via the exothermic reaction:

$$ {}^6_3\mathrm{Li} + {}^1_0\mathrm{n} \longrightarrow {}^3_1\mathrm{H} + {}^4_2\mathrm{He} + 4.8\,\mathrm{MeV} \qquad (3)$$

Thus, if a mixture or a combination of ${}^6_3\mathrm{Li}$ and ${}^2_1\mathrm{H}$ (such as lithium deuteride—the hydride of lithium in which the hydrogen is deuterium, ${}^2_1\mathrm{H}$) is heated to a high enough temperature, reactions (2) and (3) take place simultaneously, with the neutrons needed for reaction (3) being provided by reaction (2) and the tritium needed for reaction (2) being supplied by reaction (3). The combined reaction may thus be written:

$$ {}^6_3\mathrm{Li} + {}^2_1\mathrm{H} \longrightarrow 2 \times {}^4_2\mathrm{He} + 22.4\,\mathrm{MeV} \qquad (4)$$

This makes ${}^6_3\mathrm{Li}$, which comprises 7.4 per cent of natural lithium, a fusion fuel.

Lithium is quite plentiful in the Earth's crust and large quantities of lithium salts are dissolved in sea-water. It is estimated that 0.01 per cent of this dissolved lithium would be enough to last some tens of thousands of years at a conversion rate of 60 TW.

Thus it seems that if controlled fusion reactors prove to be technologically feasible, they would in the long run be able to supply the world's energy requirements for a very long time.

But, as with fission reactors, the problem with fusion reactors is likely to prove to be one of limited practicable rates of development. Fusion reactors would obviously be very complex, require sophisticated technology and high capital investment. Even if a first prototype reactor can be made to work within the next decade or so, experience with fission reactors shows that it is a very long way from that first step to large-scale application.

As with fission power, the *energy cost* of fusion power is likely to limit severely its practicable rate of development. And, as you will see in Section 4, limits other than those of resources may restrict power conversion from either fission or fusion.

Thus it seems that energy capital sources, whether fossil fuels or nuclear fuels, are most unlikely to meet a primary energy demand that rises from about 7 TW in the 1970s to about 70 TW a century later. This is because of a combination of constraints: recoverable supplies of the raw materials from which the fuels are

obtained are not unlimited; the capital cost (in energy terms) of development imposes a limit on the rate of development; the lead times—from first prototype to large-scale application of new technologies (such as fusion)—are long. Furthermore, as you will see in Section 4, environmental hazards are likely to impose even more severe constraints on the use of energy capital sources, in the long-term, 'steady-state', situation as well as in the transitional period of the next century.

3.3 Energy income sources

In this Section we review a range of energy sources that are, for all practical purposes, renewable and unlimited. We shall restrict ourselves to the main principles and an appraisal of the energy conversion potential of each source, but you will find more technical details and further reading references in the *Technical Supplement*. There are three renewable energy sources—solar energy, geothermal energy and tidal energy. Of these, solar energy is by far the largest and most important, and we shall consider it first.

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Solar energy may be converted *directly* to end-use energy or it may be converted *indirectly*, via one or more intermediate forms of energy. These conversion paths are summarized in Figure 5. The top two paths are direct and the bottom seven are indirect.

3.3.1 Direct solar energy conversion

Averaged over the whole of the Earth's surface and over a whole year, the *insolation*—which is the solar energy incident per second on each square metre on the Earth's surface—is approximately $180\,\mathrm{W\,m^{-2}}$. In equatorial regions, the annual average is about double that, and the peak solar flux at noon on a clear summer's day can approach $700\,\mathrm{W\,m^{-2}}$.

insolation

The Earth's surface area is about $5 \times 10^{14}\,\mathrm{m^2}$, so the total solar power flux at the surface is, as you can work out for yourself, very large indeed—approximately 9×10^4 TW. If ways can be found of collecting even a small fraction of this solar energy and converting it into appropriate forms of end-use energy, most, if not all, human energy needs could be met from this source.

In the first category of *direct solar energy* conversion, illustrated in Figure 5, the energy is converted into heat, for example for water heating, space-heating, cooking, or industrial process heating. Such uses account for quite a high proportion of the total end-use energy in industrially developed countries, about 40 per cent in the U.S.A., for instance.

direct solar energy

Direct solar energy technologies may be described as either *active* or *passive*. An example of the former would be the use of solar panels to collect solar energy, which is then stored as heat energy and used later for space or water heating. Another example would be the use of solar cells to generate electricity for lighting or other special purposes. An example of *passive* direct solar energy technology would be in house design that makes the maximum use of available solar energy by the best orientation of the house, location and design of windows, heat insulation, etc. In the first two examples, a device actively converts the solar energy into some convenient form of end-use energy. In the last example, the design of a passive receptor of solar energy (the house) is optimized to make maximum use of the available energy.

active direct solar energy technology

'passive' direct solar energy technology

Solar energy can be converted *directly* into electrical energy by using photoelectric cells. Photocells use special materials, called *semiconductors*, in which photons of sufficient energy transfer electrons from one part of the atomic substructure of the material to another, from which they can be collected in the form of an electric current*. They use specialized and somewhat exotic materials, and their efficiency is rather low—between 4 and 12 per cent of the solar energy can be converted into electrical energy. Consequently, large areas are needed to convert solar energy into an appreciable amount of electrical energy. For instance, one would need an area of about $6\,\mathrm{km^2}$ to generate 100 MW of electrical power with 10 per cent efficiency from solar energy at $180\,\mathrm{W\,m^{-2}}$.

photoelectric conversion (of solar energy)

* This was demonstrated in the TV programme associated with Unit 9.

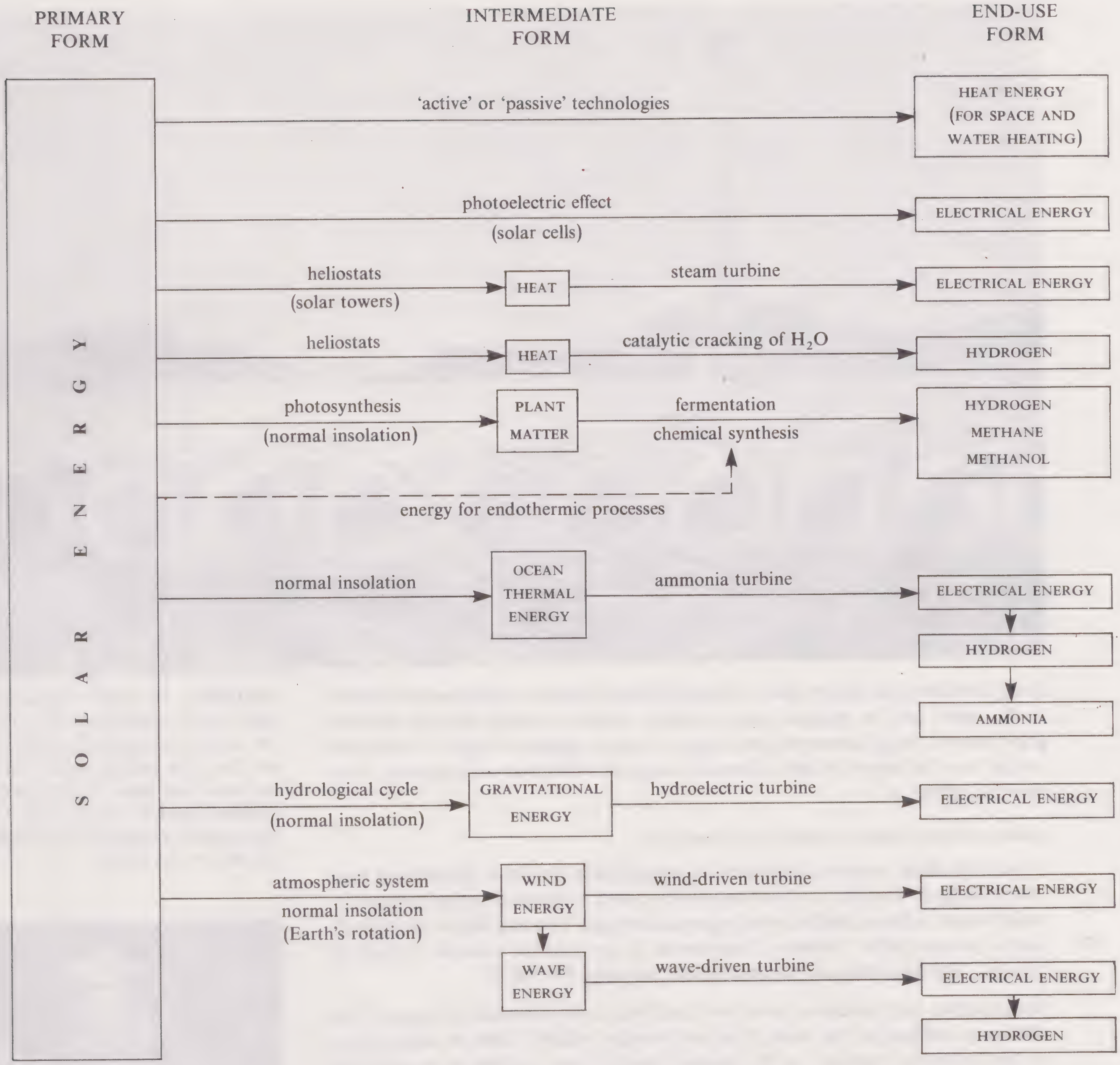


FIGURE 5 Solar energy conversions. The top two conversion paths are examples of *direct* conversion of solar energy. All the others are examples of *indirect* conversion.

Thus, the prospects of this form of direct solar energy conversion do not seem promising, except perhaps for specialized local purposes. ('Solar panels' of photocells are the most common means of providing satellites with electrical power.)

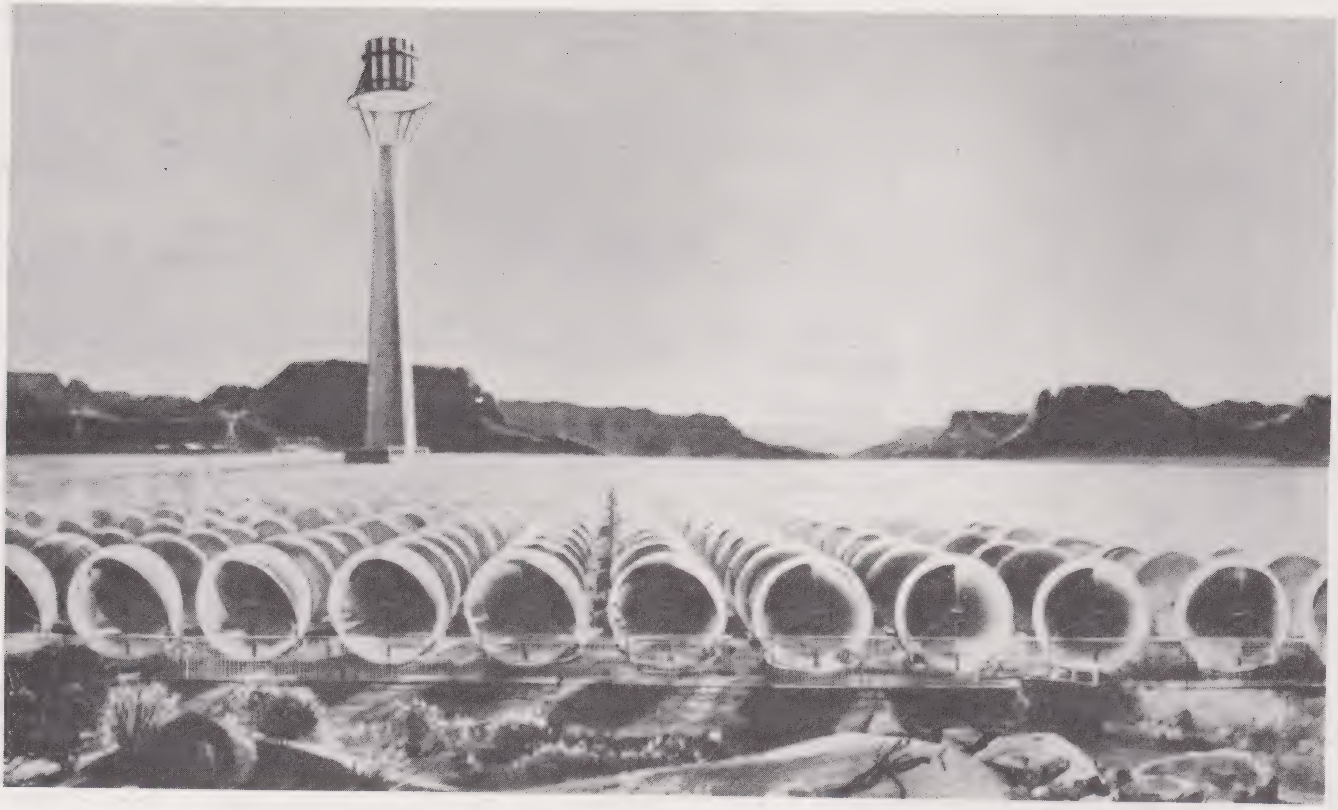
3.3.2 Indirect solar energy conversion

The first indirect conversion process shown in Figure 5 is perhaps the simplest in principle—the use of solar energy to produce steam and hence electricity.

'Solar tower power'

An array of mirrors is used to focus the sunlight on a solar furnace located in a high tower (Figure 6). The mirrors 'track' the position of the Sun and thus stay focused on the solar furnace throughout the day. The receiver cavity in the solar furnace operates at a high temperature in the range of 600–1 000 °C and generates high-pressure superheated steam which drives a conventional steam turbo-generator. It is currently estimated that solar-electric systems of this kind should achieve efficiencies, averaged over long operating periods, of about 15 per cent. But such a scheme still has the inherent disadvantage of requiring a large land area.

Since solar-electric systems cannot generate at night or during periods of very cloudy weather, they need some form of energy storage. There are several ways of



doing this: the heat energy can be stored in heated rocks or melted salts; alternatively, water can be pumped into a storage reservoir during the day and the gravitational energy converted into electrical energy during the night; or the solar energy may be converted into chemical energy in a fuel, such as hydrogen. One possible system is:

FIGURE 6 An artist's impression of a 'solar tower' installation. An array of convex mirrors automatically track the sun and focus the sunlight on the furnace at the top of the tower. Superheated steam produced there is used to drive a turbine and generate electricity in the building at the base of the tower.

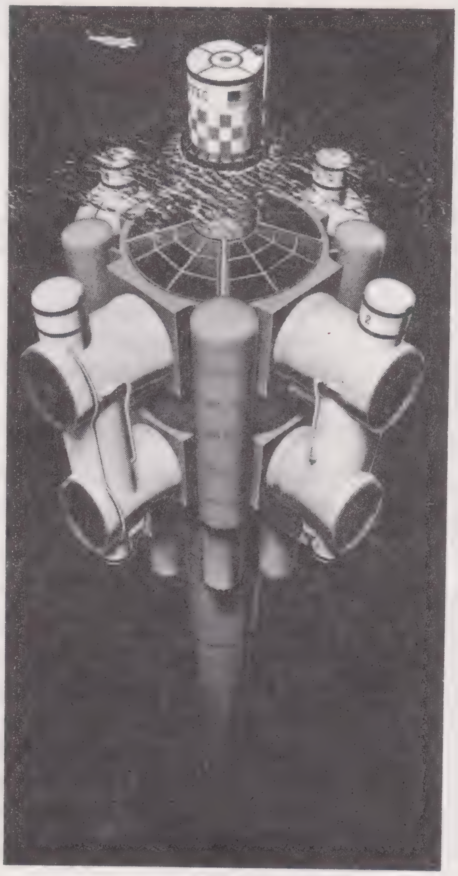
Solar-powered hydrogen generation from water

A possible direct conversion process of considerable potential importance uses solar energy to provide the heat required to work a thermochemical process in which water is dissociated into hydrogen and oxygen. You will find an example of
TS such a process in the *Technical Supplement*. It uses iron(II) chloride ($FeCl_2$) as catalyst. The temperatures required are in the range 90–900 °C.

Several other such processes have been described in various scientific papers. The efficiency—defined as the ratio of the heat energy available from the combustion of the hydrogen produced to the thermal energy input required to produce the hydrogen—varies between 40 and 60 per cent. The hydrogen can be transported by pipeline, like natural gas, or it can be converted to methanol by combining it with CO_2 or CO. This, however, implies a hydrocarbon feedstock to provide the CO_2 or CO. Such hydrocarbons are being synthesized continually by plants.

Synthetic fuels from organic plant matter

Historically, *wood* has for centuries been the most important source of stored solar energy available to humanity, and for many poor countries it probably still is. It has been estimated that potential global power capacity from the combustion of wood might amount to a maximum of 3 TW. Wood is only part of the enormous volume of plant matter produced by photosynthesis. The most fuel-starved regions of the world happen also to be the tropical regions of high rainfall and high solar energy flux. About 3.3×10^{10} tonnes of biomass, with an energy content of over 5×10^{20} J are produced by photosynthesis each year in these regions, which is equivalent to a continuous power of 17 TW—more than double the world's total power conversion in 1975. Of course, only a small fraction of this large source of energy could be used without serious risk to the environment, but world-wide photosynthesis stores between ten and twenty times as much energy per year in plant matter as is being converted by combustion of fossil fuels. Thus, even if only a small fraction of the biomass accumulated by photosynthesis could be converted into convenient fuels, we would have a potential renewable energy source of major importance.



This can be done in a variety of ways (you will find some of the details in the
TS *Technical Supplement*). For example, organic material can be converted by anaerobic fermentation into *methane*, which can itself be used as a gaseous fuel, or be

FIGURE 7 An artist's impression of a projected ocean thermal energy conversion plant, operating between ocean levels at 25 and 5°C.

converted into *methanol*, a liquid at ordinary temperatures. Alternatively, steam at high temperature can be used to break down the organic material into *hydrogen* and carbon dioxide. Again, the hydrogen can either be used as a gaseous fuel, or it can be combined with CO or CO_2 to produce methanol.

All these processes, apart from the fermentation one, are endothermic, and so increasing the temperature increases both the rate and the equilibrium yield of the reaction. The energy required for this purpose could come either from combustion of part of the product (e.g. hydrogen or methane), or from solar energy.

There have been several recent studies in the U.S.A. of the economics and technologies of synthetic fuel production from organic wastes. The estimated cost per joule of producing hydrogen from crop residues, for instance, turns out to be about the same as the current cost of natural gas in the United States. The quantities of organic waste materials potentially usable for synthetic fuel production are large. In the U.S.A., for instance, the estimated energy potential of organic wastes is about half the present primary energy conversion. The production of synthetic fuels from organic waste materials may well prove to be one of the major methods of indirect solar energy conversion.

Another indirect solar energy conversion process that may make a comparable contribution to meeting the global energy demands of the next century is ocean thermal energy conversion.

Ocean thermal energy conversion

ocean thermal energy

The principle of ocean thermal energy conversion is extremely simple. The idea is to operate a *heat engine*—a device that transforms heat energy into mechanical energy—between the warm upper layer and the cold deep water of the tropical oceans. The mechanical energy is then converted by an electrical generator into electrical energy. The power thus converted may be called *solar sea power* because solar radiation would rapidly restore to the upper layer the heat energy that is transferred to the cold deep water and converted into electrical energy.

heat engine

Figure 7 shows schematically an artist's impression of a possible solar sea power plant operating at ocean levels between 25 °C and 5 °C, and Figure 8 shows the essential features of such a power conversion system*. A fluid with a low boiling temperature, such as ammonia, carries heat energy from the boiler to the condenser via the turbine, where some of the heat is converted to mechanical energy. The

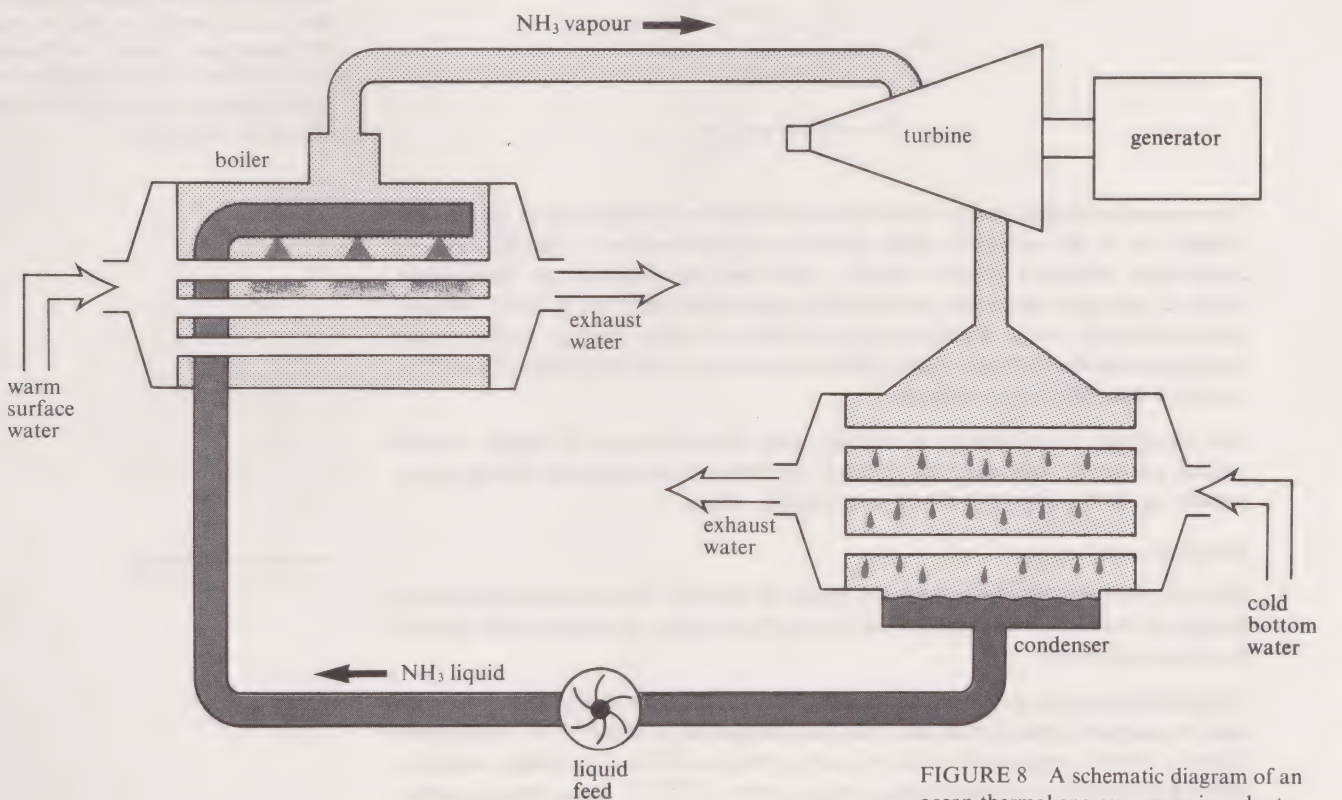


FIGURE 8 A schematic diagram of an ocean thermal energy conversion plant. Ammonia is assumed to be the working fluid in the boiler, turbine and condenser. Freon might be a preferable alternative.

* You will see a scale model of this plant in TV 32.

high-pressure ammonia vapour drives the turbine, giving up a small fraction of its thermal energy in the process. It is then condensed and returned to the boiler.

Detailed estimates have been made of the cost of electricity generated by an ocean thermal power station of this type. It seems that the cost per kW may well be quite a bit lower than that of nuclear-electric power. Since electrical energy could not easily be transported from an ocean thermal power station to the shore, it would probably be converted into hydrogen by electrolysis of the sea-water. The hydrogen could then be liquefied and transhipped to tankers, or it could be combined with nitrogen (by the Haber-Bosch process, which you learned about in Unit 15) to produce ammonia. The nitrogen fixation plant would be on the floating ocean power platform, as illustrated in Figure 9.

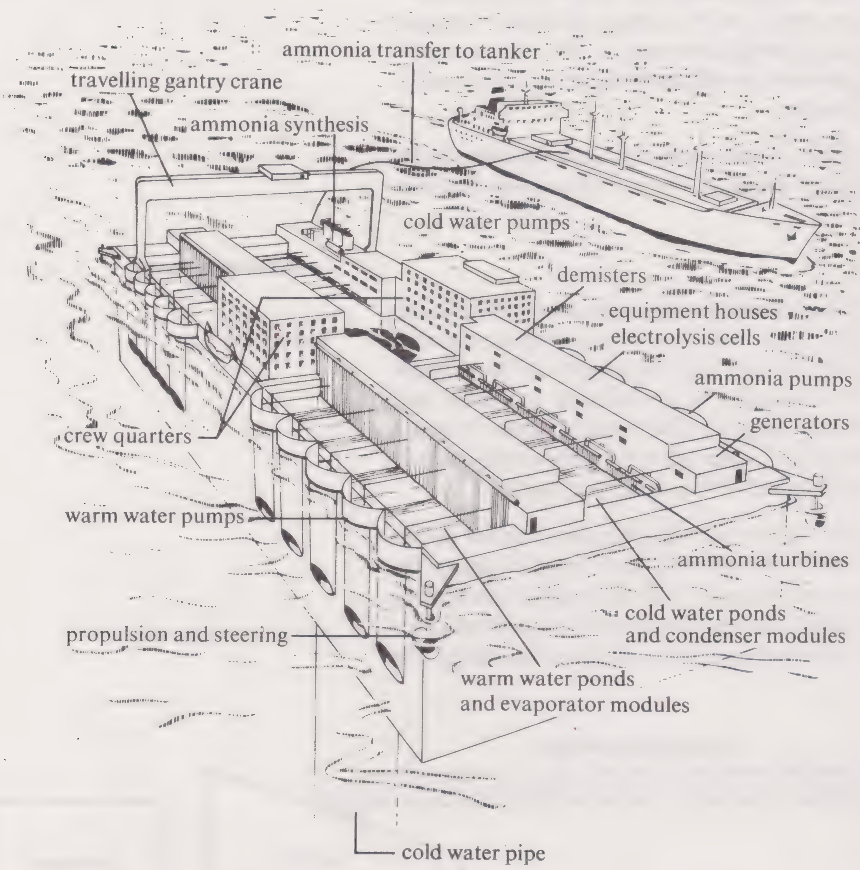


FIGURE 9 An artist's impression of an ammonia-producing factory ship grazing tropical ocean waters. The electrical energy produced by the ocean thermal energy conversion plant is used to produce hydrogen by the electrolysis of water. The hydrogen is then combined with atmospheric nitrogen to make ammonia, which is then transferred to tankers for shipment.

The ammonia could then be used either for fertilizer production or for energy storage. As it has relatively poor ignition and combustion properties and its combustion products would include toxic (and environmentally dangerous) oxides of nitrogen, ammonia is not itself a convenient fuel, but it could be converted relatively easily (by reversing the Haber process) back to nitrogen and hydrogen, and the hydrogen used directly as a fuel or combined with CO or CO_2 to produce methane or methanol.

The remaining three sources of indirect solar energy shown in Figure 5 have limited potential, although the first of the three, hydroelectrical energy, is *at present* by far the largest indirect solar energy source.

Hydroelectrical energy

hydroelectrical energy

The indirect origin of *hydroelectrical energy* is the solar energy transferred in the process of evaporation of water from the Earth's surface. Its intermediate form is gravitational energy.

World hydroelectric power capacity in the mid-1970s amounted to some 150 GW, and the ultimate potential capacity has been estimated at about 3 TW. The former figure is about 2 per cent of world primary power in 1975 and the latter would be about 4 per cent of a projected steady-state power of 70 TW. Thus, though particular hydroelectric projects may have great importance for particular countries, the global contribution of hydroelectricity is likely to remain relatively small.

Wind energy

wind energy

Part of the solar energy incident upon the Earth is converted to kinetic energy of motion of the atmosphere. It has been estimated that the energy being transformed by the Sun in this way amounts to a total power capacity of about 10^8 TW in the winds over the whole globe. Since windmills can tap only the energy available in a layer of air at most a few tens of metres high, and because air has such a low density that wind cannot provide a concentrated source of energy, only a minute fraction of the total wind power is even theoretically available. The maximum theoretical potential of wind energy has been estimated at about 300 GW. Its practical potential is probably an order of magnitude less.

Thus wind power is unlikely ever to make a significant contribution to global power conversion. That is not to say that on a smaller, local scale, wind power will not make a useful contribution to a diversified energy conversion system.

Wave energy

wave energy

Some of the energy in the world's winds is converted into energy of ocean waves. The amount of power in a wave train can be estimated by calculating the change of potential energy as the water in a wave above average sea-level falls into the trough in front of this wave. Calculations for the Atlantic show that at locations such as the western approaches of the Hebrides, annual average wave powers of between 20 kW and 60 kW per metre width of wave front could be extracted by an installation of reasonable depth. The technical problem of wave power generation is to convert the kinetic energy of the wave motion into rotatory motion of a turbine. The problem has been solved in principle and working models have been built. Large-scale application is likely to be limited, however, by the engineering problems of building and maintaining, under very severe working conditions, the many large installations that would be needed to make a significant contribution to primary energy needs. For example, to supply only ten per cent of the 1975 U.K. power conversion of 274 GW, one would need nearly 700 floating installations each 1 km long!

This concludes our brief review of the possibilities of solar energy conversion. In terms of present-day knowledge, it seems that the most significant possibilities are direct conversion to heat for space and water heating, and the first four examples of indirect conversion shown in Figure 5, 'solar tower power', the production of hydrogen from water, the production of synthetic fuels from organic matter, and ocean thermal power.

Of the two other renewable energy sources we mentioned at the beginning of this Section—tidal energy and geothermal energy—the former is of minor practical importance, but the latter may prove to be a major energy resource.

3.3.3 Tidal energy

tidal energy

The source of tidal energy is the gravitational energy of the Earth–Moon–Sun system. As the oceans move back and forth under the influence of the gravitational forces of the Moon and the Sun, the kinetic energy of motion of the water is converted into heat, mostly through friction between water and land. Thus gravitational energy is converted into heat energy. It has been calculated that gravitational energy is thus converted into heat at the rate of about 3 TW.

The object of a tidal power project is to capture some of that energy and transform it into electricity before it is converted into heat through tidal friction. If *all* this tidal energy could be converted with an efficiency comparable to that of one of the world's existing tidal power plants (La Rance, France), namely 25 per cent, this would represent a significant contribution to the possible end of the century demand of 18 TW. Unfortunately, the sites suitable for large-scale tidal power projects are few and far between, and their total capacity is estimated at less than 0.1 TW.

3.3.4 Geothermal energy

geothermal energy

What large-scale processes observable at the Earth's surface show that an enormous amount of heat is being generated in the Earth's interior, and what is the origin of this heat energy?

The whole process of sea-floor spreading and plate tectonics is driven by the decay of radioactive isotopes, principally within the Earth's crust and mantle. The

continuing processes of mountain building, metamorphism and volcanism, and all seismic activity, are all due to the conversion of nuclear energy into heat within the Earth (Units 6 and 7, 27 and 28).

Apart from these more spectacular effects of geothermal energy, there is a steady outflow of heat through the Earth's surface. It is remarkably constant over the whole Earth, averaging about $0.05\,\mathrm{W\,m^{-2}}$, which is about 3 600 times less than the solar power flux at the Earth's surface.

In certain parts of the globe, however, the heat flow is very much higher than average—up to six times greater in some places. These are the areas of present-day seismicity and volcanism, which, as you know, are concentrated along constructive and destructive plate margins.

Any volcanic area will have a higher than average heat flow simply because hot magmas are rising through the crust. If such an area is also underlain by thick rock sequences that are permeable to groundwater flow, and if the groundwater can circulate freely through them, it will be heated by magmatic bodies at shallow crustal depths. Surface manifestations of this process, called thermal areas, are characterized by hot springs, geysers and related phenomena. Geothermal energy obtained from such areas is sometimes called *hydrothermal energy* (i.e. energy from hot water). Since the volcanic activity in a given region can last for millions of years (for example, Iceland has been a volcanic region for some 15 Ma), such thermal areas provide a renewable energy resource.

hydrothermal energy

With the exception of Iceland, almost all the geothermal power stations now in operation, planned or under construction, lie near presently or recently active destructive plate margins, most of them round the Pacific; however, their total capacity amounts to only 1.6 GW.

An alternative approach to geothermal energy may add considerably to its potential capacity. At sufficient depths, rock that is hot enough to be a potentially useful energy source exists everywhere, but it is usually too deep to reach economically using current technology. However, in some areas, rock at temperatures of 200 °C or higher may be only 3 km below the surface. A recent survey of heat flow data in the western U.S.A. indicated that an area of about $2.5 \times 10^7\,\mathrm{km}^2$ is underlain at a depth of 5 km or less by hot dry rock at temperatures above 290 °C. This is a high enough temperature to produce electricity with a reasonable efficiency (30–40 per cent). Lower temperature rock, about 100 °C or so, could be used to heat water for low-temperature uses such as space-heating, food processing and manufacturing.

hot dry rock

You will find a description of a hot dry rock scheme in the *Technical Supplement*. The essential principle is simply to drill two holes that intersect in the hot rock, pump cold water down one and extract steam from the other.

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As a potential source of energy, hot dry rock is evidently very large indeed. The main limitation of this method of extracting geothermal energy is likely to be the cost of the drilling operations. There is much experience of drilling for oil or gas, but special techniques are needed to drill at depth through hard, hot rock. It is still too early to appraise the practicability and cost of geothermal energy from hot dry rock, but this may well prove to be a significant energy source in future.

3.3.5 Energy income—summary

Some of the energy sources reviewed are likely to contribute only a small amount to global primary energy, even though they may have relatively greater importance for particular countries or regions. Examples of these are wood, and hydroelectrical, wind and wave energy.

Direct solar energy conversion and the indirect production of electricity or fuels from solar energy seem to be capable of very large-scale application, and may ultimately be sufficient to meet the world's entire end-use energy requirements. Whether the contribution of geothermal energy will be small and localized or large and widespread depends on the outcome of hot dry rock experiments, which have only just begun.

There are two features of energy income sources as a whole that are worth noting. The first is their diversity and suitability for decentralized, small- to medium-scale energy conversion systems, as distinct from centralized large-scale ones. In this, they contrast sharply with nuclear energy, which is inherently large scale and centralized, and essentially nuclear-*electrical*. The second feature is that energy

income sources are almost entirely non-polluting and likely to have much less environmental impact than energy capital sources. (This point is developed further in Section 4.)

Objectives of Section 3

Now that you have reached the end of Section 3, you should have achieved the following Objectives:

(a) You should be able to explain in simple terms (or distinguish between correct and incorrect explanations of) what is meant by: energy capital, energy income, renewable/non-renewable energy, fuel, stored energy (Section 3.1); 'burner' and 'breeder' nuclear reactors, conversion ratio, a fast breeder reactor (Section 3.2); the solar energy flux at the Earth's surface, 'active' and 'passive' direct solar energy conversion, indirect solar energy conversion, 'solar tower power', ocean thermal energy conversion, production of fuel from organic matter, hydrothermal and hot dry rock sources of geothermal energy (Section 3.3).

(b) You should be able to distinguish between approximately correct and grossly incorrect statements about:

(i) the proportion of primary energy currently obtained from energy capital sources;

(ii) the capacity of energy capital sources to meet specified energy demands;

(iii) the potential contributions of energy income sources to possible future energy demands;

(iv) the distinction between direct and indirect solar energy;

(v) the essential principles of a nuclear (fission) reactor;

(vi) the production of plutonium in nuclear reactors;

(vii) why there might be a limit on the rates of development of nuclear power;

(viii) materials that are potential fuels for nuclear fusion reactors;

(ix) why hydroelectrical energy, wind and wave energy and ocean thermal energy can be described as 'indirect solar energy';

(x) the distinction between hydrothermal and hot dry rock sources of geothermal energy.

SAQ 3 (*Objective* (a)) Which of the following are correct explanations or uses of the italicized term(s)?

1 A *breeder reactor* is one in which the *conversion ratio* is greater than unity.

2 A *fast breeder reactor* is so called because it breeds new fissile material at a fast rate.

3 The *solar energy flux* at the Earth's surface is the average amount of energy per square metre per second that reaches the Earth's surface.

4 The conversion of solar energy into electrical energy by photoelectric cells is an example of *passive direct solar energy*, since no moving parts are required.

SAQ 4 *Objective* (b)) Which of the following statements are correct, or approximately correct?

1 Most of the primary energy conversion in the world comes from non-renewable sources.

2 Whereas fossil fuels are unlikely to meet a steady-state demand of 60 TW for more than one or two centuries, this demand could be supplied from the fission of $^{235}_{92}U$.

3 Breeder reactors would in principle be capable of supplying indefinitely a projected steady-state demand of 60 TW.

4 The most important potential energy income source is wind power.

5 The conversion of solar energy into synthetic fuels, such as hydrogen, methane and methanol, is likely to make a significant contribution to the end-use energy needs of the future.

6 Coal and wood are both examples of indirect solar energy.

7 The energy equivalent of estimated coal reserves is considerably greater than that of estimated oil reserves.

8 All nuclear (fission) reactors contain moderator material to slow down the neutrons so that they can be captured by fissile nuclei.

9 Breeder reactors produce $^{239}_{94}Pu$, but burner reactors do not.

10 $^{239}_{94}Pu$ is produced in both breeder and burner reactors, but $^{240}_{94}Pu$ is produced only in breeder reactors.

11 The rate at which nuclear power stations can be built is likely to be limited by the energy cost of building and fuelling them.

12 $^{6}_{3}Li$ may be an important fuel for nuclear fusion reactors because energy can be released from the fusion of $^{6}_{3}Li$ and $^{2}_{1}H$.

4 Environmental problems

4.1 Introduction

We have now established that in spite of great uncertainties about future power requirements there are very few options by which these requirements can be met.

All options require that in the *immediate* future we must continue to rely heavily on fossil fuels. They differ in the main sources of power that eventually replace the fossil fuels. There is the option in which nuclear power stations (fission and/or fusion) supply our long-term needs. There is the option in which solar power—in its various forms, and operating through various devices—supplies our long-term needs. And there are various options which mix solar power and fossil fuels.

What are the environmental implications of these various options? Are we free to burn fossil fuels, to burn nuclear fuels, or even utilize solar power, at *any* rate, or do environmental hazards impose an upper limit?

There are two sorts of environmental hazards that will concern us: climatic change, which is discussed in Section 4.2, and the non-climatic hazards associated with nuclear energy, which are discussed in Section 4.3.

These Sections far from exhaust the ways in which human activities carry environmental hazards, even if we restrict ourselves to hazards associated with energy use. But these Sections do cover some very important hazards, and ones that are particularly closely related to the choice of a power option for the future.

4.2 The effect of human energy usage on the Earth's climate

4.2.1 The Earth's climatic system

The Earth's climatic system was briefly discussed in Unit 28, Section 6. Here, we need to emphasize two things. First, that climatic change, if it occurs over a sufficiently short time, can cause considerable economic, agricultural and social disruption. This is true regardless of whether we merely suffer the consequences of climatic change, or make a rapid adaptation to the new climate. Second, that the Earth's climatic system is so complicated and so poorly understood that, at present (1979), climatic predictions are subject to considerable uncertainty.

substantial climatic change

That modest climatic change can cause considerable disruption is apparent from Figures 10a and b. To these two examples one can add many more that lead us to an estimate of what we shall term *substantial climatic change*, that is, a degree of change under which most of us would feel the pinch. Roughly speaking, it corresponds to annual mean temperature changes of greater than about 1 °C, changes of a few per cent in rainfall, and so on. If such changes occurred over less than a few decades, then adaptation to the new climate would be difficult and result in considerable disruption. It is important to realize that, to be called 'climatic changes', such changes must be *lasting*. Over the past few decades, we have experienced the odd year or two when summers were hotter or drier than usual, and winters colder or wetter. These are not climatic changes, but fluctuations that are always present within a given climate. No substantial climatic changes have occurred over the past few decades.

Clearly, it would be of considerable advantage to be able to predict the sort of future climatic changes that would be consequent upon the adoption of various global energy policies. Is this, in fact, possible?

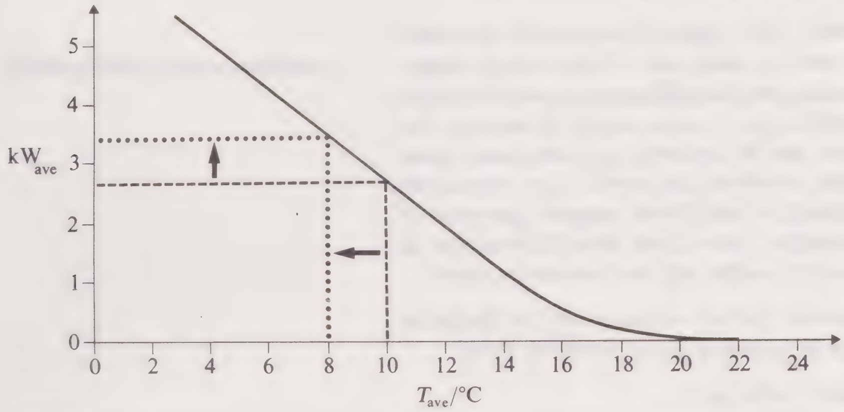


FIGURE 10 (a) The approximate effect of mean annual air temperature (T_{ave}) on the mean annual power (kW_{ave}) needed for space-heating a typical U.K. semi-detached house, insulated to current Building Regulations standards, with a typical ventilation rate, and enjoying a reasonable indoor temperature. Note that a decrease in 2 °C of present U.K. mean outdoor temperature results in about 30 per cent increase in mean power requirement.

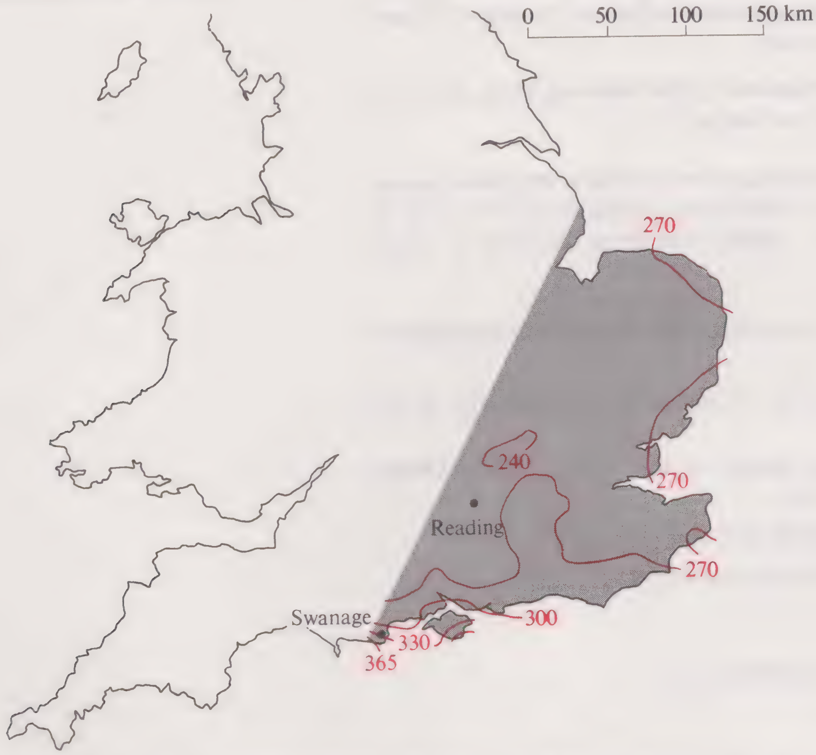


FIGURE 10 (b) The contours show the length of the growing season in days per year. This is the number of days in an average year over which an 'average' crop will grow, and is therefore closely related to agricultural yield. South-east England has been chosen because it is a region without large altitude changes. The values shown thus correspond to different climates at comparable altitudes. Though the difference in climate between Swanage and Reading is not dramatic, the growing season falls from 365 days per year (the maximum possible) to about 270 days per year.

The climate of a region depends on a very large number of factors. It depends on vertical energy exchanges between the ground and various levels in the atmosphere, and on horizontal energy exchanges between the region in question and every other region of the Earth. In an analogous manner the climate of a region depends also on the vertical and horizontal exchanges of *matter*, particularly water vapour, clouds and dust. It depends also on the detailed geography of the whole Earth, and on the transport of energy by the oceans, and so on. Moreover, all these things interact with each other. Thus, for example, the mean water vapour content of the atmosphere over the Midlands (U.K.) depends, in part, on the mean Antarctic snow cover. Conversely, Antarctic snow cover depends, in part, on the mean water vapour content of the atmosphere over the Midlands.

Simple models of such a complex system can give quite misleading results, especially because such systems can behave in a *counter-intuitive* manner. For example, it is possible that an increased flow of energy into the Earth's climatic system can actually lead to a *lowering* of temperature in certain regions!

climate model

Climatic models, which attempt to reflect this jungle of complexity, are called *general circulation models*, and they need to make use of the world's largest computers. But it is still necessary to make gross simplifications in order to obtain results from these models in a reasonable time i.e. in a matter of months. For example, heat transported by the oceans may be neglected, or 'small-scale' phenomena, such as thunderstorms, are either completely neglected or are represented in a highly simplified way. Another difficulty is our almost complete ignorance of certain key interactions. How, for example, does cloud cover depend on air temperature? Nobody really knows, so the models rely on 'educated guesses'.

general circulation model (climate)

Nevertheless, general circulation models are the best we have, and it is likely that they do at least predict climatic change to within a factor of two or three.

After studying Section 4.2.1 you should be able to:

(a) State, briefly, what is meant by substantial climatic change, a general circulation model.

(b) Recognize that many aspects of our lives are sensitive to climate.

(c) Appreciate that (i) the Earth's climatic system is very complicated; (ii) certain aspects are poorly understood; (iii) climatic predictions (because of (i) and (ii)) are subject to considerable uncertainty.

To test whether you can meet these Objectives try the following SAQs. (SAQ 5 is more of an exercise, based on general knowledge.)

> **SAQ 5** (*Objective* (b)) Write a brief account of all the disruptions you can imagine being consequent upon a fall of winter temperatures in the U.K. by the few degrees necessary to ensure that snow becomes a winter commonplace.
>
> **SAQ 6** (*Objective* (c)) Which of the following events might influence the climate of the U.K.?
>
> (i) Increased volcanism resulting in increased dust content of the atmosphere.
>
> (ii) The Gulf Stream (a warm current in the North Atlantic Ocean) shifting south and missing the U.K.
>
> (iii) The wind pattern over central Asia changing.
>
> (iv) China doubling its annual energy conversion.

4.2.2 The problems of environmental heat, aerosols and CO_2

Environmental heat

The net effect of almost all present energy use by humanity is to release energy from a fossil fuel or nuclear fuel, use it, and transfer it to the environment in the form of heat. One example of such a conversion was given in Unit 8, Section 11, and you can probably think of several more. You may also remember from that Unit that the principle of conservation of energy ensures that we cannot create (or destroy) energy. But we are releasing it from where it has long been 'locked' in the chemical bonds or nuclear bonds of fossil fuels and nuclear fuels. This energy, and indeed all energy that we use, from any source, is ultimately transferred to the environment in the form of heat. This ultimate end-product of our energy usage is called *environmental heat* (often called *waste heat*).

environmental heat (waste heat)

Is the *rate* at which environmental heat is being generated now, or in the foreseeable future, sufficiently high to pose a climatic threat?

Currently (1979), environmental heat is being generated at the *rate* of about 8 TW. If this is to pose a threat to climate, then it must be significant when compared with the *rate* at which natural energy sources place energy in the Earth's climatic system.

There is only one such major natural input—from the Sun. The average rate at which solar energy is absorbed globally by the Earth's atmosphere and surface is

1.2×10^5 TW*. By comparison, even the flow of energy from the Earth's interior (mainly heat from radioactive sources) pales into insignificance, at about 250 TW. How much more, therefore, does *our* present input, of 8 TW seem to pale into insignificance! But is it insignificant? And in any case our input is growing. At what level may it pose a threat?

General circulation models have been used to investigate the problem of environmental heat. The indications are—and this is in part our own interpretation of the results of various studies—that were the global rate of release of environmental heat to reach about 100 TW, then substantial climatic change would probably occur over an appreciable fraction of the Earth's surface. However, the nature of this change in any particular region is unknown. Bearing in mind the uncertainty of climatic modelling, it is likely (but not certain!) that the true figure that would induce change lies between 50 TW and 200 TW, that is between about 0.05 per cent and 0.2 per cent of the global solar input.

The 69 TW projection in Figure 3 is of the same order as 100 TW. Moreover, there may be no time delays to come to our assistance: climatic change would follow closely in the wake of any rise in environmental heat. We thus have some reason to believe that it is environmental disruption, and not the rate at which fossil fuels or nuclear fuels can be made available, which determines the maximum rate at which we can burn such fuels.

To minimize environmental heat we must clearly minimize our use of fossil and nuclear fuels or, more generally, of *capital* sources. The most fundamental way in which this could be done would be to replace, as far as possible, the burning of fossil/nuclear fuels by solar energy. The extensive use of solar energy would not appreciably increase the energy input to the Earth's climatic system. At worst, it would result in a *redistribution* of energy. For example, solar energy may be used in June in Arizona to dissociate water and produce hydrogen, and this hydrogen, or a fuel produced from it, is burnt in January in Boston and Milton Keynes. Heat which would have been present in Arizona in June, thus appears as environmental heat in Boston and Milton Keynes in January. This redistribution would have some climatic effect. Although no detailed study has yet been made of this type of problem, the *feeling* among climatologists is that *redistributing X* watts of power is likely to have appreciably less effect on global climate than releasing an additional *X* watts into the Earth's climatic system.

aerosol

Aerosols

Another by-product of our energy usage is *aerosols* (i.e. suspensions of solid or liquid particles in the atmosphere). You are probably familiar with aerosols from spray cans. The aerosol (under pressure) is released as a spray of small liquid droplets, carrying the paint or scent (or whatever) to the place where it is needed. These familiar aerosols form a small and short-lived fraction of all artificial aerosols. But large, and long-lived fractions, originate from fossil fuel burning, smoke being the most familiar, but there are many other kinds as well.

Aerosols influence climate because they alter the energy exchanges between the Sun and the atmosphere, and between the atmosphere and the ground. So complicated are their effects, and so poorly understood, that at present one study leads to one conclusion, whereas some other study leads to a very different conclusion. Moreover, as yet, no general circulation model has been used to study the effect of aerosols on global climate, and so, at present, we can only consider whether it is at all *feasible* that artificial aerosols *could* influence climate.

There is no doubt that most common natural aerosols—droplets of water, or tiny crystals of water ice (usually in the form of clouds)—have a profound influence on climate. However, water aerosols released by human activities are negligible compared with the natural background, and therefore we must consider aerosols *other* than water. Figure 11 compares the 1970s rate of release of aerosols by natural processes (excluding water) with the rate of release of all artificial aerosols (also excluding water). It is at once apparent that artificial aerosols are being released at a significant rate compared with natural aerosols. The atmospheric content depends on rates of release and rates of removal. We do not appear to have appreciably changed removal rates. Therefore, we are probably giving rise to an increase in the aerosol abundance of the atmosphere.

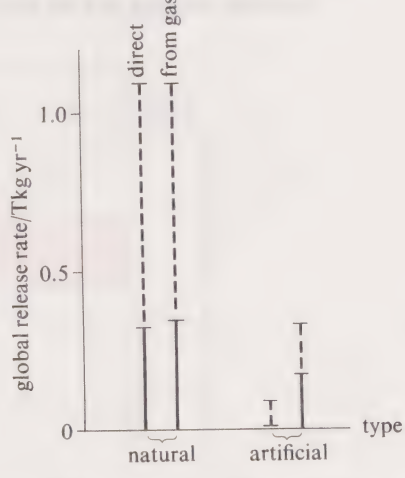


FIGURE 11 Global rates of release of aerosols. Approximate upper and lower limits are shown, indicating present (1979) uncertainties. The rates given correspond to particles smaller than 40 µm diameter. 'Direct' aerosols are those released in the form of aerosols (e.g. smoke), whereas 'from gas' aerosols are released as gases, which then give rise to aerosols. (*Note* 1 Tkg = 10^{12} kg. In order to avoid inflicting yet another strange prefix upon you, we are departing from the internationally agreed convention according to which the prefix should not be attached to kg but to g, in spite of the kilogram and not the gram being the SI base unit. According to the convention, the quantity 10^{12} kg (i.e. 10^{15} g) should be called a petagram (Pg).)

* The figure of 9×10^4 TW given on p. 22 is the energy reaching the *surface*, and does *not* include that absorbed by the atmosphere.

Some climatologists believe that fluctuations in the natural atmospheric abundance of (non-water) aerosols have contributed to *past* climatic changes (see Unit 28, Section 6). It is thus conceivable that *artificial* aerosols are being released at a rate sufficient to cause substantial climatic change in the not too distant future. It is a problem worthy of closer examination.

Carbon dioxide

Carbon dioxide is a by-product of the combustion of fossil fuels (see Unit 15), the CO_2 being released into the atmosphere as a gas. The clearance of biomass, and the subsequent burning or decay of the cleared material, also releases CO_2 into the atmosphere. In this regard, forests are by far the most important bio-material. Conversely, forest regrowth removes CO_2 from the atmosphere, the CO_2 being incorporated in tree tissue via the process of photosynthesis (see Unit 21). But, a *stable* forest has negligible effect on CO_2 because new growth (photosynthesis) is matched almost exactly by *respiration* and *natural decay* (see Units 21 and 14)*.

greenhouse effect

Atmospheric CO_2 influences climate via the so-called *greenhouse effect*. This is an effect whereby the surface temperature of a planet is raised because atmospheric constituents are more transparent to solar radiation than to the longer wavelength infrared radiation from the planet's surface. Solar radiation is concentrated at visible wavelengths. If the atmosphere is reasonably transparent to such wavelengths, then much of it reaches the ground. There it is absorbed, and re-radiated at much longer wavelengths. If at these wavelengths the atmosphere is more opaque, then energy is trapped near the planet's surface, and the surface temperature is raised. In the case of the Earth, the greenhouse effect itself is responsible for a rise in mean global surface temperature from a frigid $-18\,°C$ to the actual $+15\,°C$. In spite of this large difference, it is almost entirely sustained by *minor* atmospheric constituents, in particular, by water vapour, aerosols, and carbon dioxide.

mean global temperature

Because CO_2 is a minor atmospheric constituent, human activities have succeeded in appreciably changing its atmospheric abundance. Figure 12 shows the atmospheric CO_2 content since 1850. Values for years before 1958 are uncertain, and this uncertainty grows as we go back in time, as indicated by the broadening of the shaded region in the Figure. But there has certainly been an increase in CO_2, and almost all of this increase has arisen from a combination of fossil-fuel burning and an excess of forest clearance over regrowth.

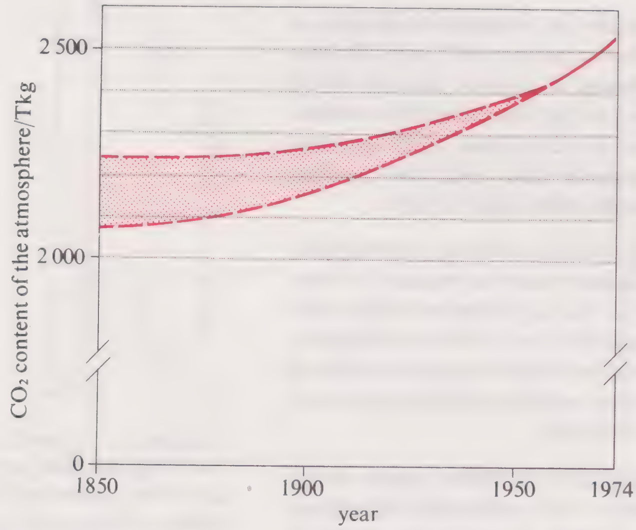


FIGURE 12 The measured atmospheric CO_2 content since 1850. This corresponds to about half the CO_2 released into the atmosphere. The 'missing' half has largely been absorbed by the oceans.

The problem of climatic change resulting from an increase in atmospheric CO_2 content is being tackled by several scientific groups, using general circulation models. The tentative conclusion at present is that an increase of atmospheric CO_2 to about one-third above 1970s levels may well cause *noticeable* (i.e. a little less than *substantial*) climatic change over most of the Earth's surface.

The best evidence currently available therefore suggests that we must limit the release of CO_2 into the atmosphere in such a way that the atmospheric CO_2

* The matching is not quite exact. Some of the CO_2, once present in the Earth's atmosphere, has been split by *net* photosynthesis into carbon (the fossil fuel deposits), and oxygen (in the atmosphere, and surface rock oxides).

content never exceeds '1970s plus one-third'. Figure 13 shows a projection in which this is achieved: the atmospheric CO_2 content rises smoothly to the allowed maximum, and stays there.

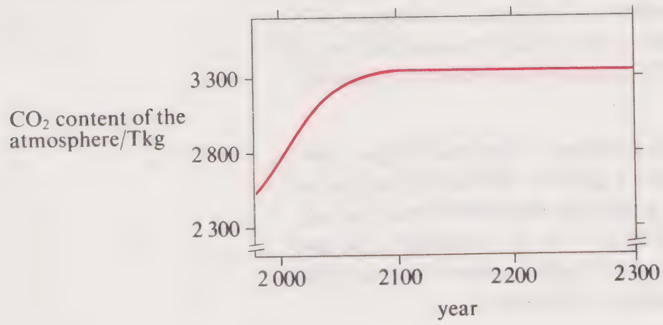


FIGURE 13 A future CO_2 content of the atmosphere, were it to rise smoothly to reach an upper limit that is probably safe, as far as climatic change is concerned.

You might think that this maximum imposes a limit on the total *amount* of CO_2 that can be released into the atmosphere. In fact, it imposes a limit on the *rate* at which CO_2 can be released, rather than on the total. The *rate* comes in because CO_2, once released, does not remain indefinitely in the atmosphere. It is removed by a variety of processes, and the atmospheric content, as in the case of aerosols, reflects a balance between release and removal. The quickest removal is by enhanced plant growth, which can remove a sudden injection of CO_2 in a matter of decades. Next come the oceans, which can remove a sudden injection in a matter of *centuries*. The role of oceans as sinks for CO_2 has been discussed in Units 14 and 28. Both oceans and plants are sinks of limited capacity. Carbonate rock formation provides a very large sink, but takes *millions* of years to remove a sudden injection of CO_2.

Figure 14 shows the important features of the future rates at which CO_2 can be released into the atmosphere *from fossil fuel burning* under the constraint that the atmospheric CO_2 content follows the curve in Figure 13. We have deliberately not put scales on the axes of Figure 14 because of the uncertain nature of the curve. There are *three* main reasons for this uncertainty. First, the details of oceanic removal of CO_2 are not fully understood—it is a complicated problem. Second, it is not known whether, in the future, there will be net forest growth, or net forest clearance. If there is net growth, this will remove CO_2 from the atmosphere, and will allow greater rates of release from fossil fuels. If there is net clearance, the rates of release from fossil fuels must be reduced. Finally, the amount of CO_2 from net forest clearance in the past 100 years is not well known and, because the oceans are still absorbing some of this, this uncertainty projects into the future.

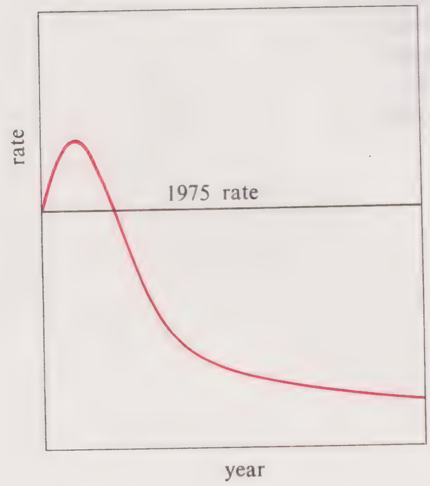


FIGURE 14 The future rate of release of CO_2 into the atmosphere, from fossil fuels alone. This curve is *not* quantitative, but it does show the main qualitative features consistent with Figure 13 and with an Earth biomass that becomes constant during the progress of the curve.

Nevertheless, Figure 14 shows the main features of the future rates at which CO_2 can be released into the atmosphere from fossil fuels under the constraints imposed by Figure 13. There can be an increase above the 1975 rate (about $17\,\mathrm{Tkg\,yr^{-1}}$) to some maximum. But then the rate must fall. This is because of the limited capacity of oceans and plants as sinks. If plants act as sinks rather than sources, then it won't take long for the increase in biomass, especially forests, to reach a reasonable limit. That leaves the oceans. But they can't even remove CO_2

at the 1975 rate of release of CO_2 from fossil fuels. So, to prevent the CO_2 content of the atmosphere from continuing to rise, the rate of release must fall, and it must fall well below the 1975 rate. It must ultimately reach a rate when, with stable forests, the release rate from fossil fuels will equal the rate of oceanic removal, and the atmospheric CO_2 content is therefore constant, as in Figure 13. Between 1975 and this future time of balance, the net release rate of CO_2 exceeds the rate of removal, and that is why the atmospheric CO_2 content rises above the levels of the 1970s.

In 1978, two scientists, U. Siegenthaler and H. Oeschger, attempted to put numbers on the axes of a graph something like that in Figure 14. The maximum rate of release of CO_2 from fossil fuels is reached in about the year 2000, and it is only about 50 per cent above the 1975 rate of $17\,\mathrm{Tkg\,yr^{-1}}$ or so. Thereafter, the rate falls rapidly, levelling out at about *one-fifth* of the 1975 rate in about the year 2300, the atmospheric CO_2 content rising in the manner of Figure 13.

This particular result—because of the problems discussed above, in relation to Figure 14—cannot be very accurate. Nevertheless, their result shows that the power projections in Figure 3 should not be met by fossil-fuel burning, with the release of CO_2 into the atmosphere. For example, to provide 69 TW from fossil-fuel burning in the year 2070, the rate of release of CO_2 from fossil fuels in that year alone would be about ten times that in 1975. This is *seven* times the *maximum* rate suggested by Siegenthaler and Oeschger, and *fifty* times the rate that they ultimately set to keep the atmospheric CO_2 content to '1970s plus one-third'. It is highly unlikely that their estimates of safe limits are too small by such large factors.

Their result also indicates that by the year 2300, if we are to stay within safe limits, we can burn less than only 10 per cent of the known reserves of fossil fuels, if we are to release the CO_2 into the atmosphere. This is an example of an environmental limit rather than a resource limit.

After completing Section 4.2.2 you should be able to:

(a) State, briefly, what is meant by environmental heat (waste heat), aerosol, greenhouse effect.

(b) Describe briefly the main sources and sinks of atmospheric carbon dioxide.

(c) Identify the approximate limits above which environmental heat, aerosols and CO_2 are likely to cause substantial climatic change.

(d) Distinguish an environmental limit from a resource limit.

To test whether you can meet these Objectives, try the following SAQs.

SAQ 7 (*Objective* (c)) On the basis of the evidence in this Unit, discuss which of the (hypothetical) scientists A, B, C, D in Table 6 have come to erroneous conclusions, and which have come to correct conclusions, regarding safe upper limits for the release rates of waste heat, aerosols, and CO_2. (For the case of CO_2, use the numerical estimates of Siegenthaler and Oeschger.)

TABLE 6

	Safe upper limits		
Scientist	waste heat/TW	aerosols/$\mathrm{Tkg\,yr^{-1}}$	$CO_2/\mathrm{Tkg\,yr^{-1}}$
A	10	0.1	2
B	30	0.3	5
C	60	0.5	10
D	150	1.0	20

SAQ 8 (*Objective* (d)) In 1978 it was suggested by Professor T. Gold that vast quantities of methane (CH_4) may be present in the Earth's outer mantle and crust, incorporated at the time of the Earth's formation. Supposing that it could be recovered, discuss, in about 50 words, why it does *not* offer a clear solution to the energy problem.

4.2.3 Conclusions

There is a significant probability that humanity's energy use will cause substantial climatic change if it gives rise to any one of the following stresses.

1 The rate of emission of environmental heat from capital sources reaches about 10 times the level of the 1970s.

2 Aerosols are released at rather greater rates than those in the 1970s.

3 Atmospheric CO_2 content reaches a level somewhat in excess of one-third above that of the 1970s.

Of these three, it is the last, the release of CO_2, that poses the most immediate threat to global climate.

If we think of these stresses as a 'prong', then fossil fuels pose a three-pronged climatic threat, nuclear fuels a one-pronged climatic threat (environmental heat only), and solar power a *zero*-pronged climatic threat, though solar power does pose a reduced threat in cases when it redistributes energy in space and time. Therefore, our present state of knowledge indicates that climatic change is least likely if the solar power option is adopted.

But, in view of the present state of climatic modelling, how much reliability can be placed on *any* of these conclusions?

An arch-optimist might argue that all the various effects of all our various activities on climate will somehow cancel out, or that natural processes will arise to neutralize each assault as it arises. Not likely! The first statement is rather like saying that if a piece of delicate and complicated equipment is clobbered in several different ways at once, its operation will be unaffected. The second statement is tantamount to claiming that the Earth's climate is invariable, whereas you know from Unit 28 that this is far from being the case. Moreover, our neighbouring planets, Mars and Venus, though made originally from much the same stuff as the Earth, now possess climates of ferocious hostility compared even with the most inhospitable parts of the Earth's surface. The Earth will not, as of right, continue to possess its present climate indefinitely.

We must admit that, at present, we cannot be certain what effects our energy usage may be having on climate. In our present state of ignorance, and bearing in mind the social disruption consequent upon rapid climatic change, it is surely wise to plan to reduce climatic stress, and at the same time make vigorous attempts to improve our understanding of the Earth's climatic system. With such improved understanding will come an ability to define more exactly to what extent we must limit climatic stress, and an ability to predict more accurately the consequences of applying large climate stresses. This then opens up the possibility of planned adaptation to new climates. However, because energy use is local, whereas climatic change is global and unequal, it may be more realistic always to aim to avoid causing climatic change. This is possible by means of more efficient energy use, thus lowering primary demand, and the adoption of the solar power option.

The question of what we do in the future is discussed in more detail in Section 5. Before that, we must discuss the (non-climatic) hazards of nuclear energy.

After completing Section 4.2.3 you should be able to outline briefly, strategies for minimizing climatic stress.

To test whether you can meet this Objective, try the following SAQ.

SAQ 9 For each strategy (A–E), identify the corresponding reduction(s) in climatic stress (1–5).

Strategy

A Encourage forest regrowth

B Switch from fossil fuels to solar power

C Implement a programme of more efficient energy use, to reduce primary demand

D Plan to adapt to climatic change

E Switch from fossil fuels to nuclear fuels

Reduction in climatic stress

1 none

2 less waste heat released

3 less aerosol released

4 less CO_2 released into the atmosphere

5 less CO_2 retained by the atmosphere

4.3 Hazards of nuclear energy

4.3.1 Radioactivity

As we explained in Section 3.2.3, all nuclear reactors—whether of the 'burner' or the 'breeder' type—produce large quantities of highly radioactive *fission products* and also large quantities of plutonium, which is a highly toxic material that also happens to be fissile and hence suitable for the manufacture of atomic bombs.

Fission products are *radioactive* because they are highly unstable isotopes with a larger neutron excess than stable nuclei of the same atomic number. They decay to stable isotopes, emitting β- and γ-radiation in the process.

Plutonium is also radioactive and, like radium or uranium, it decays, with a half-life of 24 400 years, by emitting α-particles:

$$^{239}_{94}\mathrm{Pu} \longrightarrow {}^{235}_{92}\mathrm{U} + {}^{4}_{2}\mathrm{He}$$

and the $^{235}_{92}$U itself decays, with a half-life of 710 Ma, through a succession of α- and β-decays to $^{206}_{82}$Pb (Units 26 and 30).

Why are radioactive materials dangerous?

They are dangerous to living organisms because the radiation they emit when decaying causes cell damage. In large doses this is fatal, in smaller doses it causes cancer and, in still smaller doses, genetic damage through mutations. The toxicity of many radioactive elements is greatly increased by the fact that they become concentrated in organisms and in particular organs within them. For example, strontium, like calcium, is concentrated in the bones, and $^{90}_{38}$Sr accordingly produces radiation damage in the bone marrow and hence leukaemia. Plutonium, like radium, tends to get concentrated in the surface layers of bones, as well as in the liver. A particularly dangerous characteristic of plutonium is that it readily forms aerosols that can be easily inhaled.

Because of the difficulties inherent in assessing the precise toxicity to man of cancer-producing poisons, there is some disagreement among the authorities about the exact quantity of ingested plutonium that is lethal. The official guidance for the maximum permissible lung burden of plutonium is about 10^{-12} kg. Some researchers have suggested that the lethal burden may be several orders of magnitude less, but this is challenged by others. The exact figure is uncertain because estimates have to be based on experiments with laboratory animals—there have so far been no clearly established human deaths from plutonium poisoning. Nevertheless, it is clear that plutonium is one of the most toxic substances known.

The fission products of nuclear reactors have half-lives ranging from a small fraction of a second to several million years. The most important ones have half-lives of less than 30 years; for instance, the half-life of $^{90}_{39}$Sr is 28 years and that of $^{85}_{36}$Kr is 10 years, but some fission products have much longer half-lives, e.g. $^{129}_{53}$I (16 million years) and $^{135}_{55}$Cs (2 million years). The resulting decay in the

relative toxicity of the mixture of radioactive wastes from a nuclear reactor (fission products plus actinides produced by neutron absorption in the original uranium fuel) is as shown in Figure 15. Though the fission products decay in a thousand years to less than 10^{-7} times their initial activity, the actinides and their daughter products, most of which have long half-lives, maintain the relative toxicity at around 10^{-3} or 10^{-4} times the initial value for more than a million years. This disparity between the two components of radioactive wastes suggests that it would be advantageous to separate the actinides from the fission products chemically and adopt different waste disposal strategies for each kind.

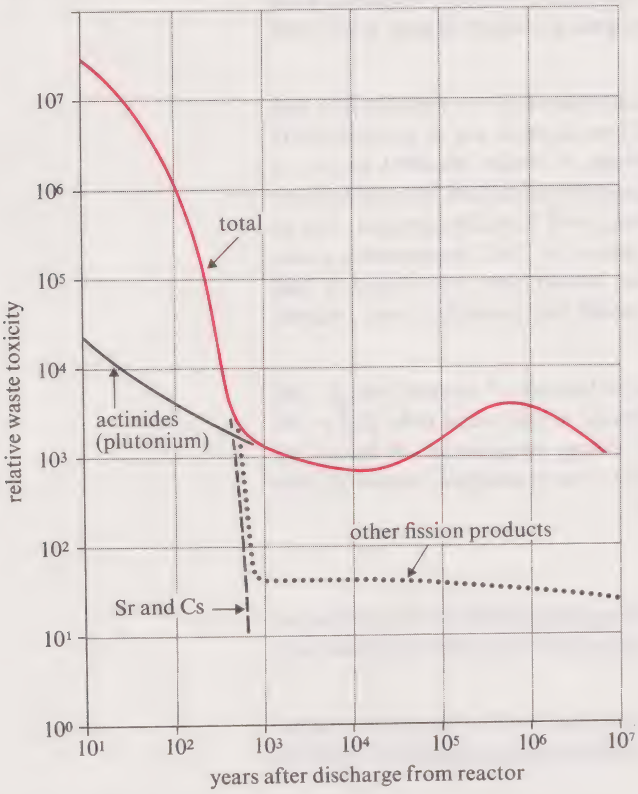


FIGURE 15 Relative toxicity of radioactive waste material from a typical nuclear power reactor. The decrease in relative toxicity has the complex form shown because the waste products include fission products like $^{90}_{38}Sr$ and $^{137}_{55}Cs$, which decay fairly rapidly, other fission products like $^{135}_{55}Cs$ and $^{129}_{53}I$, which have much longer half-lives, and also actinides like $^{239}_{94}Pu$ and $^{230}_{94}Pu$, which have long half-lives and which also have radioactive daughter products. The increase in relative toxicity around 10^6 years is due to the growth of these daughter products. The curves are calculated on the assumption that 95.5 per cent of the uranium and plutonium has been removed from the waste material before disposal.

The quantities of fission products produced in a nuclear power reactor are very large. To take but one of the more dangerous isotopes, a 1-GW reactor produces about 30 kg of $^{137}_{55}Cs$ per year (3 per cent of the yearly reactor fission products). The official guidance for a maximum body burden of $^{137}_{55}Cs$ is about 10^{-12} times that amount. However, in assessing the significance of these figures, it should be kept in mind that what is important with radiological poisons, as with chemical poisons (such as chlorine), is not merely their toxicity and the relatively large quantities involved, but the actual probability of some fraction of the material reaching human beings. Furthermore, it should be appreciated that the official 'permissible' body burden of caesium, for instance, is very low; it would have to be maintained for about 40 years to give a 2 per cent chance of producing cancer and, as caesium is excreted fairly rapidly, the body burden would last only a few months and the cancer risk due to the 'permissible' burden would be reduced to about 1 in 5 000.

The high toxicity and the long lifetimes of both fission products and plutonium evidently require that their containment must be total and quasi-permanent, at all stages in the reactor fuel cycle. The possible release of radioactive material into the biosphere is evidently one of the environmental hazards of nuclear energy.

Of course, the nuclear energy industry is well aware of this problem and is exerting great efforts and technical ingenuity to find more effective methods of containment. The requirement of *quasi-permanent* effectiveness is, however, a technological challenge without precedent. It is, of course, true that some highly toxic chemicals present similar containment problems, and that it is necessary to find effective ways of containing these materials too. The problem of containment of dangerous materials used in certain microbiological research activities has led governments of several countries to impose severe restrictions on some of these activities and to ban some altogether.

It is important to appreciate the scale of the problem. There is a tendency on the part of some advocates of large-scale development of nuclear energy to quote the

good safety record of the industry over the past few years and the relatively small numbers of accidents, injuries and deaths that have so far been recorded—incomparably smaller than the numbers in the coal mining industry, for example.

However, by 1975, nuclear power contributed only about one per cent of the world's total power (i.e. about 0.1 TW) but is expected by the advocates of the nuclear option to contribute at least half the total by the end of the first quarter of next century (i.e. at least 25 TW) and practically all of this total by the end of that century (i.e. perhaps 70 TW or more). So, as yet, we have only just started on the nuclear energy road. And, as the record of the 'incidents' that have occurred in the nuclear energy industry shows, there have been quite a number of near misses and narrow escapes*.

The other important point to appreciate is that because of the high toxicity and long lifetimes of reactor products, the risk to containment are of a *qualitatively different kind* from those of any other technology. A major accident in, say, a petrochemical plant, can produce instant damage and casualties, but within a few years all material traces and most human damage will have disappeared. Not so with a major accident in a nuclear power station or fuel reprocessing plant. Most of the human victims of such an event would not even know it had occurred until afterwards, and indeed many could not possibly know, because they would belong to unborn generations.

It is this unique aspect of the specific long-term hazards of nuclear energy that makes it so difficult to make a reasonable estimate of the social risks and social benefits of a large-scale, fission-based nuclear energy programme. Whereas the social benefits can be quantified in terms of a cost–benefit analysis, the social risks have ethical aspects that cannot be quantified.

4.3.2 Direct hazards of nuclear energy

The direct hazards of nuclear energy are evidently primarily due to the problem of containment of radioactive materials within the nuclear fuel cycle and after they have been rejected as wastes.

Failure of containment seems most likely in three phases of the fuel cycle: reactor operation, transport of irradiated fuel and reprocessing of irradiated fuel. We shall consider each of them briefly.

Operational safety of reactors

There is considerable controversy, even among experts, over both the risks of an accident to a nuclear reactor and the possible environmental consequences of such an accident.

The optimists believe that appropriate design can reduce the risks of accident to a negligible level. The pessimists believe that the problem is not merely one of good engineering design but of human fallibility. However, the nuclear energy industry is exceptionally conscious of industrial risks, and very elaborate precautions are taken in the design of reactors to minimize this. And it is certainly true that 'there has not yet been an accident with a commercial installation sufficient to have constituted an operational or environmental catastrophe, though there have been some "near misses"'**.

Flowers draws the conclusion that 'it is fair to say of the commercial reactors at present operating in the United States and the United Kingdom that, megawatt for megawatt, the nuclear industry is much safer than the coal industry'.

In the event of a major break in the containment system of a nuclear reactor—whether caused by an accident, by sabotage or by an act of war—the casualties and the areas of territory rendered uninhabitable for some time afterwards depend very much upon the exact siting of the reactor relative to populated areas, whether evacuation of the population can be carried out in time, the prevailing weather and details of the accident itself. Consequently, expert opinion again

* See for instance Walter C. Patterson (1976) *Nuclear Power*, Chapters 6 and 7, Penguin. A more recent example (1979)—the accident to the reactor near Harrisburg, Pennsylvania—attracted much public attention and caused the U.S. President to order a special enquiry into reactor safety.

** From an article by Lord Flowers (then Sir Brian Flowers) in the *Bulletin of the Atomic Scientists*, March 1978.

varies over quite a wide range. At the optimistic end of this spectrum one finds judgements such as that of Lord Flowers:

> . . . the most likely outcome would be a few hundred deaths from various forms of cancer and serious evacuation and clean-up problems for perhaps 30 miles downwind, with an outside chance that it might be ten times worse. Disastrous, certainly, but not out of proportion with the risks an industrial nation faces from many of its other activities or even from natural causes. Thus, a nuclear program should not be regarded as unacceptable as far as the safety of its thermal reactors is concerned, especially as safety in design is continually improving.

At the pessimistic end of the spectrum, we find estimates of fatalities of many thousands, radiation injuries to even greater numbers and serious contamination (not just 'clean-up problems') of several thousand square kilometres.

The problem of reactor safety has the peculiar features that an accident has very low estimated probability but very severe (and to an insurer, costly) consequences. This has led to unique legislation—in the United States of America, the United Kingdom and other countries—which limits the liability of nuclear reactor operators for third party damages to a very small fraction of the amount that would be claimed in the worst case.

It should be emphasized that these estimates refer to *burner* reactors. The safety problems of *fast breeder reactors* are generally accepted to be very much more severe, and the consequences of an accident orders of magnitude more serious. (The reasons for this are discussed briefly in the *Technical Supplement*.) **TS**
Flowers comes to the conclusion that 'The key to safety lies in the design process itself, so that the design and construction of a commercial scale reactor at the appropriate time would itself be an important step in assessing whether the required level of safety can be achieved in practice. But it is also clear that the present state of knowledge about the safety of fast breeder reactors does not allow one to rely upon a continuing FBR programme'.

Safety in transport of reactor materials

The nuclear fuel cycle involves several transport operations. Spent nuclear fuel elements are transported (after a sojourn in 'cooling ponds' to allow the most radioactive fission products to decay sufficiently) to a reprocessing plant. After recovery of the plutonium, new plutonium fuel elements are transported back to the reactor.

The risks of transporting nuclear reactor materials are not calculable in detail but they will certainly increase as more nuclear power plants are built, especially with a plutonium economy and the associated shipment of fuel that has been allowed to cool only for a short time. If nuclear power is to meet a significant proportion of the global demand then, with an annual production of several thousand tons of plutonium, there will be thousands of shipments each year.

Safety of nuclear fuel reprocessing plants

At the twenty-third Pugwash Conference on Science and World Affairs*, held in Finland in 1973, a working group of twenty-one scientists from fourteen countries studied the problem of radioactive pollution and issued a report on Fission Energy Problems and Alternatives. It concluded that 'it is possible that fuel-reprocessing plants may be more vulnerable to accidents than reactors. They are safer than reactors in that the potential for internal energy release is much smaller, but more dangerous in that some of the barriers of the reactor against release of fission products are no longer present (fuel element cladding, reactor vessel) and in that the fuel-reprocessing plant necessarily covers a much larger area'.

4.3.3 Indirect hazards of nuclear energy

These are at two levels: (a) the diversion of reactor materials for purposes of financial gain (through blackmail or resale), or for purposes of terrorism; (b) the

* Since 1957, the Pugwash Conferences have brought together about one hundred of the world's most distinguished scientists, many of them with major responsibilities as scientific advisers to their governments, to consider problems such as peace keeping, security, arms control and disarmament, population, environment and resources, and the social responsibility of scientists. The influence of these conferences, through their participants, has been considerable.

overt or covert diversion of reactor materials by national states for the purpose of producing nuclear weapons.

Criminal diversion risks

Certain facts must be taken into account in any assessment of the risks of 'diversion' (theft) of nuclear materials by terrorist groups, non-nuclear governments (or their agents), lunatics, criminal syndicates or speculators.

(i) A few kilograms of $^{239}_{94}Pu$, in a suitable chemical form, can be made into a crude nuclear weapon.

It is *not* necessary, for the purposes of an 'unofficial' weapon-maker, that he should acquire '*weapon-grade' uranium or plutonium**. According to Dr. Victor Gilinsky, of the U.S. Nuclear Regulatory Commission, 'reactor-grade' plutonium can be used 'for nuclear warheads at all levels of technical sophistication . . .' When reactor-grade plutonium is used there may be a penalty in performance that is considerable or insignificant, depending on the weapon design. But . . . even simple designs, albeit with some uncertainties in yield, can serve as effective, highly powerful weapons—reliably in the kilotonne range**.

'weapon-grade' uranium or plutonium

A home-made weapon that failed to achieve a high explosive yield (by nuclear weapon standards)—for instance, of only a few tons instead of a few thousand tons of TNT equivalent—could still do great damage, both from blast and from the effects of radiation emitted at the instant of explosion and of the dispersed plutonium.

(ii) Burner reactors produce only slightly less $^{239}_{94}Pu$ than do breeder reactors of the same power. A typical 1-GW burner reactor makes several hundred kilograms of $^{239}_{94}Pu$ every year. In a nuclear energy programme based on breeder reactors, the plutonium must necessarily be recovered and recycled, and this would increase the risks of diversion. But it would be wrong to imagine that if there were no breeder reactors there would be no diversion risk.

(iii) Current methods of reprocessing fuel from nuclear reactors separate plutonium from uranium and fission products, and store the purified plutonium in one of several chemical forms. In the manufacture of fission bombs by nuclear powers, these forms are converted to plutonium metal. This operation is within the capacity of a competent metallurgical chemist with radiochemical experience and fairly modest laboratory facilities. However, a crude fission bomb could probably be made from plutonium dioxide, PuO_2, which is one of the major forms in which plutonium is stored. In this case then, no chemical operation would be necessary.

Thus a few kilograms of reactor-grade plutonium in one of the present stored chemical forms could probably be made in less than a year into a crude nuclear weapon by a physicist, a chemist, and a small group of technicians, using techniques thoroughly described in published texts.

Because of the dangers of illicit fission-bomb manufacture, the nuclear energy industry is working on new systems of fuel reprocessing. In these new systems, very little plutonium would ever be separated from non-fissile uranium ($^{238}_{92}U$). In addition, the plutonium would be deliberately contaminated with selected fission products that are intensely radioactive. Under these conditions, the handling of the plutonium would need very sophisticated equipment such as remote handling devices in specially constructed concrete caves. Illicit fission-bomb manufacture by small groups would then become extraordinarily difficult. However, such measures are not yet operational, and their technological and economic practicability is not yet established. Moreover, for purposes of terrorism or blackmail it is not really necessary to make a nuclear weapon (for which several kilograms of plutonium would be required). A few *grams* of plutonium, whether adulterated or not, judiciously combined with a normal chemical explosive device would constitute a most dangerous weapon. The release into the atmosphere of a densely populated area of even a few grams of plutonium, dispersed in the dust of a 'conventional' explosion, could be disastrous.

* Weapon-grade means a concentration of $^{235}_{92}U$ or $^{239}_{94}Pu$ of about 90 per cent or higher. Reactor-grade plutonium has less than 90 per cent $^{239}_{94}Pu$, the rest being $^{240}_{94}Pu$.

** A weapon in the kilotonne range means one with an explosive power equivalent to that of 1–10 kilotonnes of TNT (a chemical explosive). The Hiroshima bomb had an explosive power of 10–20 kilotonnes.

(iv) Methods of 'safeguarding' reactor materials such as plutonium have, of course, been developed at both national and international levels, for instance by the International Atomic Energy Agency. But these are aimed primarily at *detecting*—through elaborate 'bookkeeping' checks on fissionable materials—their 'loss', or theft, and make no claims on preventing this from happening, or on recovering lost or stolen materials. The systems that have been developed are thought to be capable of accounting for the material to an accuracy of 1 per cent. Within this 1 per cent error, fissionable materials could, in principle, be 'diverted' without detection.

To make a bomb in the kilotonne range, one would need about 5 kg of pure $^{239}_{92}Pu$, or perhaps four times as much reactor-grade plutonium. A single 1-GW reactor produces about 250 kg of plutonium per year. So, if nuclear reactors were to supply energy at the rate of, say, 25 TW, the undetectable 1 per cent would be enough to make about 3 000 kilotonne-range bombs *per year*.

(v) The problem of safeguarding nuclear materials has some features in common with safeguarding other materials or objects that are highly valuable or dangerous or both—such as banknotes, bullion, heroin and commercial airliners. Though they are very costly and thorough, these safeguards are not fully effective.

It may well be possible to apply more costly and thorough safeguards to nuclear materials so long as the nuclear energy industry remains a relatively small-scale affair. However, on the scale implicit in a nuclear-powered future, efficient and perpetual control of nuclear materials would require strict police control of the entire world. This would be very difficult to achieve and does not convey a very attractive picture of a future society.

Of course, sites other than nuclear fuel reprocessing plants, and materials other than plutonium are also potentially attractive targets for terrorist attack or 'conventional' acts of war. Large stores of liquid natural gas or of chlorine are examples that come to mind. It is evident that a technical civilization cannot be built without some concentration of risk. The question is whether we must inevitably add yet another, peculiarly severe, risk to the ones we already have.

Risks of national-state diversion

We are concerned here with the risk that—with large-scale nuclear-electrical power plants operating in most, if not all countries—many more of them will overtly or covertly make nuclear weapons. There is a consensus among the major nuclear powers and among arms control specialists that this *proliferation of nuclear weapons* constitutes an even greater danger than the continuation of the strategic nuclear arms race*. Indeed, it has been argued that the two dangers are not independent: the continued strategic arms race has impeded adhesion to the Non-Proliferation Treaty and has at the same time led the 'nuclear powers' to energetically sell 'peaceful' nuclear technology to the non-nuclear powers** and, in the likely event of nuclear weapons being deployed in some regional conflict, there is a far from negligible risk of the major nuclear powers becoming involved, with devastating consequences not only to themselves but to the rest of the world as well.

proliferation of nuclear weapons

The fact must be faced that any country with a significant nuclear power capacity can—without advanced technology and at a trivial cost—produce nuclear weapons, and that by refraining from using weapons-grade plutonium, any such country can divert reactor-grade plutonium from the fuel cycle to produce nuclear weapons without great risk of detection.

* The strategic nuclear arms race has led to the stockpiling by the major nuclear powers (U.S.A. and U.S.S.R.) of many thousands of 'strategic nuclear weapons'. These are mostly thermonuclear (fusion) weapons with explosive powers in the range 250 kilotonnes to several megatonnes.

** One of the articles of the Non-Proliferation Treaty imposes on the 'nuclear' signatory powers (U.S.A., U.S.S.R., U.K.) an obligation to take effective steps towards nuclear disarmament. Their failure to do any such thing has been used as an argument by non-signatory powers (e.g. India) against signing the Treaty. The nuclear powers tend to placate the non-nuclear ones by telling them 'you mustn't make nuclear weapons, but we'll help you make nuclear power stations'.

(This point is lucidly explained by R. A. Falk in an article quoted by Lovins, pp. 177–8. See Appendix 1, reference 5.)

4.3.4 Conclusions

The disquiet about plans for large-scale nuclear power felt by increasing numbers of scientists has been expressed by Dr Hannes Alfvén, the Swedish Nobel Laureate in Physics:

> Fission energy is safe only if a number of critical devices work as they should, if a number of people in key positions follow all their instructions, if there is no sabotage, no hijacking of the transports, if no reactor fuel processing plant or reprocessing plant or repository anywhere in the world is situated in a region of riots or guerilla activity, and no revolution or war—even a 'conventional one'—takes place in these regions. The enormous quantities of extremely dangerous material must not get into the hands of ignorant people or desperados. No acts of God can be permitted.*

Of course, it is true that the nuclear energy industry is making great efforts to minimize the dangers and is devising precautions that will certainly reduce them, though this may add considerably to the cost of nuclear power.

This, however, poses a problem of stability. The proponents of a nuclear energy future believe that massive additional dangers can be counteracted by massive additional precautions. Their critics argue that the consequences of a light imbalance between such large opposing forces would be much more dangerous than would be the case in the non-nuclear option, where both the dangers and the precautions would be very much less.

The environmental hazards of fossil fuels (not to mention the hazards to the workers in the fossil fuel industries) are also very great. It is at least arguable that converting chemical energy from fossil fuels at the rate of tens of terawatts is as dangerous as converting nuclear energy at the same rate. Each has its specific environmental hazards, and both carry the ultimate risk of overheating the biosphere. It should not be assumed, however, that the alternative energy income sources will be without any environmental hazards, though they seem likely to be much less serious than those of fossil or nuclear fuels.

So what conclusions can be drawn from this brief examination of the environmental hazards of large-scale nuclear power? It may turn out that current efforts to reduce these hazards to an acceptable level will be successful, and that nuclear fission may be able to bridge the gap between the depletion of fossil fuels (or the severe restriction on their combustion that might be imposed by climatic hazards) and the development on a sufficiently large scale of alternative energy technologies. Or it may turn out that the hazards of fission-based nuclear energy will be considered to be too great to be acceptable and alternative technologies will be developed with greater urgency. At all events, it seems that a future 'steady-state' global energy strategy should not be based primarily on nuclear fission.

If this conclusion is correct, we seem to be faced with an insoluble contradiction: the climatological and other hazards of both fossil-fuel and fission-fuel energy seem so serious that it may not be prudent to convert energy from either of these two sources at a very much greater rate than the present global power of about 7 TW. On the other hand, politically realistic assumptions about population growth and economic development indicate that the demand for power by the middle of next century may be much greater, perhaps ten times as great.

4.3.5 Fusion—a postscript

Can this contradiction be resolved? This is the question we consider in the final Section of this Unit. But before we move on to that, we should say a word about the potential hazards of energy from nuclear *fusion*.

The extremely complex technology of controlled fusion devices and the correspondingly long lead-times that must be expected from laboratory to commercial prototype—and hence to large-scale application—suggest that fusion is unlikely to be a significant option until well into the next century. It is not out of the question, however, that fusion might at some time be able to make a significant contribution to a diversified energy conversion system relying primarily on direct and indirect solar energy. So would it be safe?

* Hannes Alfvén (1972) Energy and environment. *Bulletin of the Atomic Scientists*, **28**, 5, p. 6.

Of course, the safety problems of a practical fusion reactor cannot be assessed without building one, but there are grounds for believing that it would be very much safer than a fission reactor. The quantities of radioactive products per unit of power output would still be large, though two or three orders of magnitude less than in a fission reactor. Fusion reactors would produce large amounts of neutron-induced radioactive materials*, comparable to those produced in the core of a fast breeder reactor. Present estimates suggest, however, that these activation products would constitute a biological hazard that would be an order of magnitude less (and of shorter duration) than that of a comparable fission reactor.

Unfortunately, the replacement of fission by fusion would not solve the problem of proliferation of nuclear weapons. A fission reactor would be a copious source of neutrons and an unauthorized addition of thorium to the lithium blanket would provide a source of $^{233}_{92}U$, which, being fissionable like $^{235}_{92}U$ or $^{239}_{94}Pu$, could be used for nuclear weapons. There is also some danger that tritium (produced from lithium by neutron bombardment) could become a strategic material when the design principles of 'pure' thermonuclear weapons eventually become common knowledge. (These do not require a fission bomb to produce the high temperature needed for a fast fusion reaction.)

Perhaps the decisive factor that will limit the use of fusion power will be the *thermal* limit (Section 4.2), which applies to any process that converts stored energy (energy capital) into heat.

Now that you have read Section 4.3 of the Unit, you should be able to:

(a) Give reasons why the environmental hazards of nuclear energy are believed to be *qualitatively* different from those of other industries.

(b) Explain why plutonium is a particularly dangerous substance.

(c) Identify some of the containment hazards of the nuclear fuel cycle.

(d) Identify the special hazards of 'diversion' of plutonium

(e) Give reasons why large-scale development of nuclear energy may cause further proliferation of nuclear weapons.

Here is an SAQ to test these Objectives.

SAQ 10 Which of the following statements about nuclear energy and its hazards do you think are:

A essentially true,
B essentially untrue,
C of debatable truth?

1 The activity of the radioactive wastes from a nuclear reactor decreases to an insignificant level after a few hundred years, and need only be contained for that length of time.

2 Radioactive materials are dangerous because they can cause genetic damage, cancer or fatal radiation sickness, according to how much is ingested.

3 If nuclear reactors can be made absolutely safe, the main hazards of nuclear energy would be eliminated.

4 Plutonium from nuclear reactors is radioactive because it is contaminated by radioactive fission products.

5 People working with plutonium are not at serious risk of lung cancer so long as they do not absorb more than the permissible amount of 10^{-12} kg into their lungs.

6 Ethical, as well as economic and technological, factors are involved in the debate about whether a fission-based energy strategy is desirable.

7 The excellent safety record of the nuclear energy industry shows that fears about the environmental hazards of nuclear energy are exaggerated.

* Neutron-induced radioactive materials are materials made radioactive by capture of neutrons.

8 The International Atomic Energy Agency has devised very efficient methods of accounting for nuclear materials, but their efficiency is not a hundred per cent.

9 Reactor-grade plutonium cannot be used to make nuclear explosives.

10 Any country with a significant nuclear power capacity can make nuclear weapons without great risk of detection.

11 The development of nuclear energy should not be confused with the proliferation of nuclear weapons, since they are separate and unrelated issues.

12 Fusion reactors would have the great advantage over fission reactors of not producing any radioactive waste products.

13 The spread of fusion reactors around the world will not increase the risk of proliferation of nuclear weapons, and this is an important advantage of fusion over fission.

14 The choice between nuclear and non-nuclear fuels is essentially between an option with major environmental dangers and one without any such dangers.

5 Is there a solution?

The dilemma facing the world's population in the coming century is illustrated in Figure 16. The uppermost curve (5) shows the increase in primary power demand that would occur, on the assumptions about growth rates that were the basis of Figure 3 (p. 9). The other curves show the conceivable contributions to the total from coal (1), coal + oil (2), all fossil fuel (3) and fossil + nuclear (4). The category 'other' includes all the other sources considered in Section 3.3.

cumulative energy demand

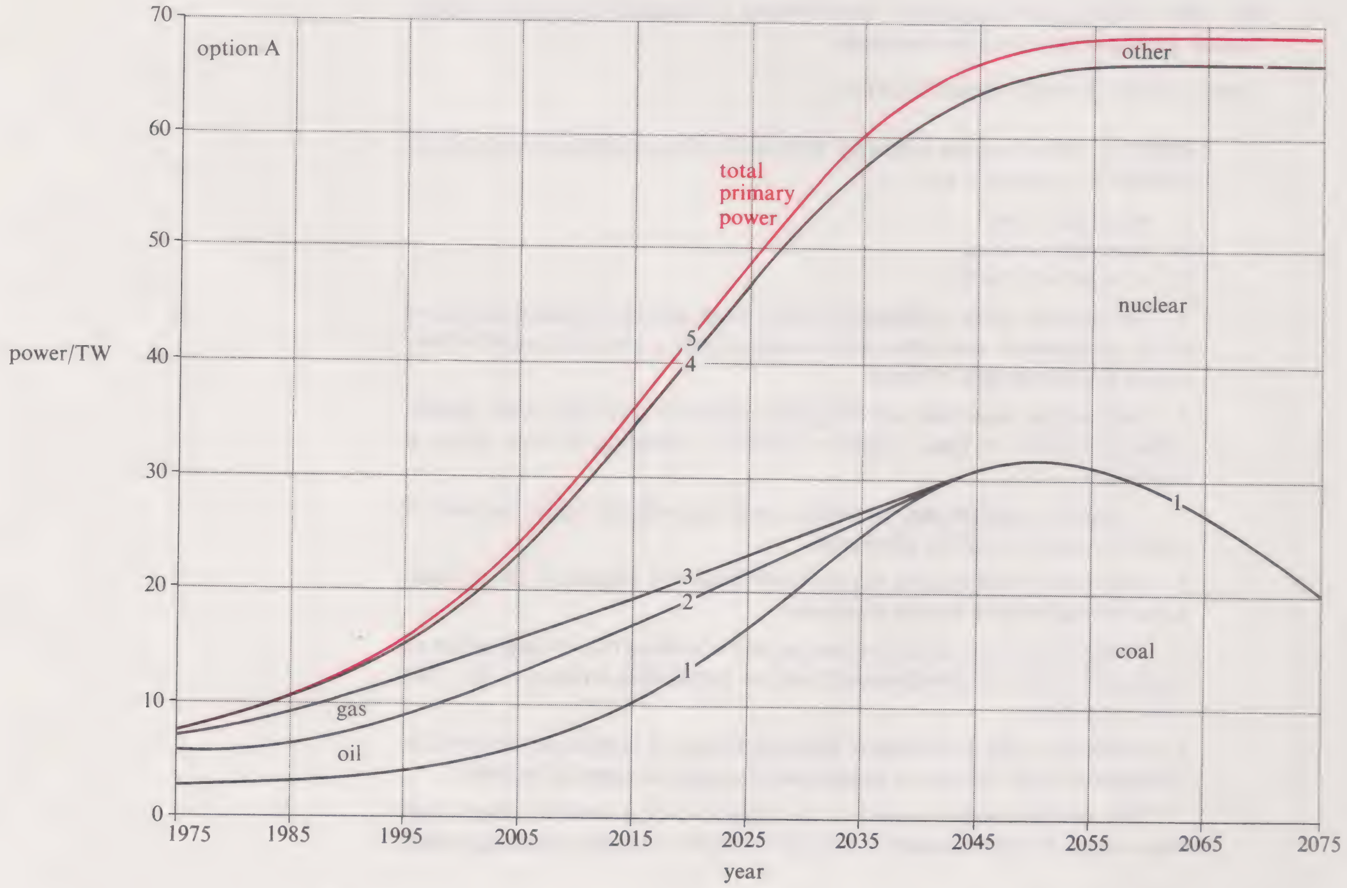


FIGURE 16 A 'hard energy strategy' for meeting a primary power demand rising to a steady state level of nearly 70 TW. The demand is met almost entirely from energy capital sources, mainly nuclear.

As oil and natural gas supplies are exhausted, and the contribution of coal increases until it too is phased out, nuclear energy increasingly makes up nearly all the rest of the total primary power. You should be aware, from the discussion in

Section 4.2 (Figure 14), that meeting such a large proportion of the cumulative demand by burning fossil fuels could have very grave climatic effects. Should this prove to be the case, it would be necessary to reduce the fossil fuel contribution—and hence increase the nuclear fuel contribution—more rapidly than is indicated in Figure 16. Yet the increase in nuclear power shown in Figure 16 is about 45 TW in 100 years, or 450 GW per year. That would mean more than one large nuclear-electrical power station coming into operation *every day* for a hundred years. Even apart from the environmental hazards of such a large nuclear programme, it is doubtful, for reasons we have already noted, that such a rapid rate of construction would be practicable.

We seem to have reached an impasse. So perhaps the thing to do is 'go back to the drawing board' and think again about the distinction between primary energy, end-use energy and functional energy. It is, after all, functional energy that people actually need for their agriculture, industry and transport, to heat their homes, cook their dinners and do other useful things. For these purposes, they need end-use energy in convenient forms appropriate to the functions for which the energy is used.

We mentioned in Section 2 (and illustrate in TV 32) some of the reasons why there is a gap between primary and end-use energy, and another gap between end-use and functional energy. One can only make a guess about the proportions of end-use or functional power in the world's total primary power of 7.3 TW in 1975. We would guess that about half the primary power is lost in conversion processes, so that 3.6 TW would be an optimistic estimate for the end-use power, and that there is a similar factor of at least two between end-use and functional power. Thus world functional power in 1975 was probably less than 1.8 TW.

Now, if these proportions were to remain fixed while primary power increased as in Figure 16, then end-use and functional power would increase as in Figure 17, with the latter flattening off at about 17 TW.

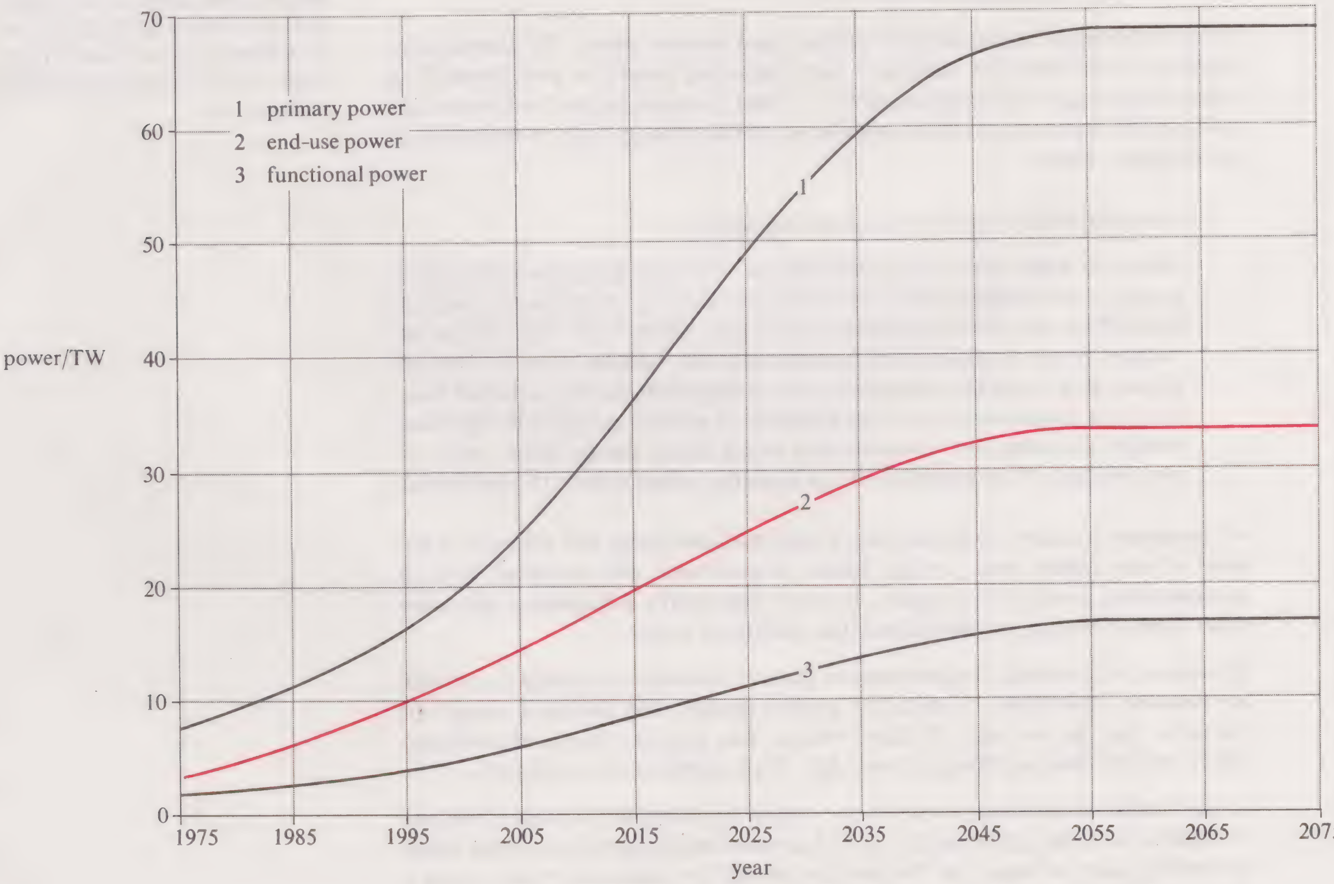


FIGURE 17 Primary, end-use and functional power projections, assuming that primary power demand is as in Figure 16 and that the ratios of primary to end-use power and end-use to functional power remain as they were in 1975.

The question you should now ask yourself is this: are there ways in which the primary power and the end-use power could be reduced, without reducing the functional power, as illustrated in Figure 18? What energy technologies would make it harder to do so? Might it even be possible to close the gap between end-use and functional power still further by keeping the end-use power at

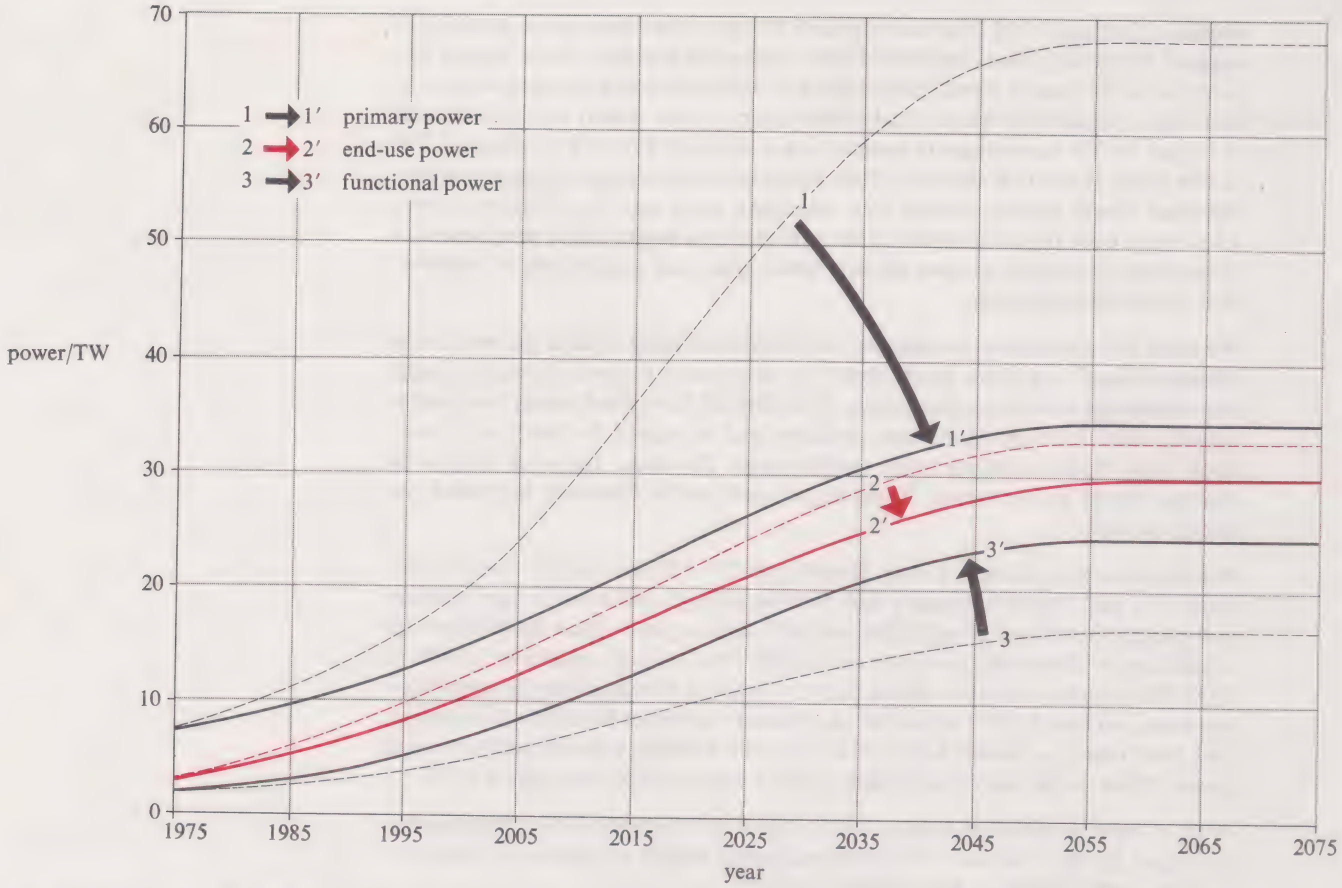


FIGURE 18 An energy strategy in which the functional power is as in Figure 18 (curve 3) or even somewhat higher (curve 3′), but both primary power (curve 1′) and end-use power (curve 2′) are substantially lower than in Figure 18.

the level of curve 2′ in Figure 18, but *increasing* the functional power from the level of curve 3 to that of curve 3′?

Think first about the gap between primary and end-use power. To illustrate the problem, think about the electricity meter spinning merrily in your home. It is measuring the quantity: (end-use power × time). For each joule of end-use energy you pay for, however, about three joules of primary energy have to be converted at the power station.

> Can you recall where the other two joules go?
>
> Mostly in waste heat at the power station—into that proportion of the heat energy in the furnace which *cannot* be converted into mechanical energy in the turbine and thence into electrical energy. (Remember that this is *not* because power engineers are incompetent, but because there is a law of physics that limits the proportion of the energy that can be converted from one form to another—e.g. from chemical or nuclear energy into electrical energy—*by being first converted into heat*.) Other energy losses occur in transmission of the electrical energy from the power station to your house.

All processes that convert primary energy into end-use energy and deliver it to the point of use involve some energy 'losses' in processing and transport. And all processes that go via a 'heat engine', in which heat energy is converted into some other form of energy, involve substantial additional losses.

So one way of reducing the gap between primary and end-use energy is to avoid, for instance, converting chemical or nuclear energy into electrical energy for purposes that do not need electrical energy. You may say that is obvious and surely nobody does anything quite so daft. Well, consider these figures:

In the United States today, about 58 per cent of all energy at the point of end-use is required as heat, split roughly 23–35 between temperatures above and below the boiling point of water. (In Western Europe the low temperature heat alone is often a half of all end-use energy.) Another 38 per cent of all U.S. end-use energy provides mechanical motion: 31 per cent in vehicles, 3 per cent in pipelines, 4 per cent in industrial electric motors. The rest, a mere 4 per cent of delivered energy, represents all lighting, electronics, telecommunications, electrometallurgy, electrochemistry, arc welding, electric motors in home appliances and in railways, and similar end uses that now require electricity.

Some 8 per cent of all U.S. end-use energy, then, and a similarly small proportion in other countries, requires electricity for purposes other than low temperature heating and cooling. Yet, as electricity is actually used for many such low-grade purposes, it now meets 13 per cent of U.S. end-use needs—and its generation consumes 29 per cent of U.S. fossil fuels. An energy strategy such as that illustrated in Figure 16 would increase the electrical component of end-use energy by a large factor.

Can you think thy this should be so?

A proportion of the primary energy in fossil fuels can be delivered as end-use energy to the point of use (e.g. gas or fuel oil to heat your house). But *all* the primary energy in nuclear fuels would have to be converted into electrical energy (or possibly into a synthetic fuel like hydrogen), *having first been converted into heat**. The proportion of primary energy on which the 'heat engine penalty' would have to be paid would, therefore, increase as nuclear fuels replace fossil fuels. This would increase the ratio of primary to end-use energy.

So it seems that *one* way of reducing the amount of primary energy needed to provide a given amount of end-use energy is to reduce to a minimum the proportion of primary energy that is converted via heat into electrical energy. Another way is to use the energy conversion and distribution processes that are the least costly, in energy terms, that is, to reduce the *energy cost* of end-use energy. The sort of question that comes up here is: which, in energy terms, is the cheaper way of delivering essential electrical energy to industry and the consumer—to build large, central, power stations and distribute the energy over large distances, or to build more, smaller, power stations closer to the point of end-use, and possibly combine electricity generation with production of steam for industrial purposes or for residential space-heating? The analysis of this sort of question is quite complex and is beyond the scope of this Unit. There are, however, some indications that decentralization and diversification of primary energy conversion processes may facilitate reductions in the ratio of primary to end-use energy.

It is also clear that if capital energy sources could be wholly or partially replaced by energy income sources, many of the energy losses inherent in the conversion of fuels could be avoided and the gap between primary and end-use energy thereby reduced. Moreover, as energy income sources are by definition renewable, and for all practical purposes unlimited, there is a less obvious need to limit the amount of primary energy that has to be converted to produce a given amount of end-use energy.

We should sound a warning note here, though. Converting solar energy into synthetic fuels, for instance, would avoid the major *global* environmental problems of fossil or nuclear fuels, for it would not add to the heat input or the CO_2 input to the atmosphere or have any of the direct or indirect hazards of nuclear energy. But it is by no means certain that it would not cause regional or local climatic or ecological problems that would have to be studied very seriously before large-scale projects were to be embarked upon.

Now consider the other gap—that between end-use and functional energy. Think again about that electricity meter in your home. You don't really pay for the pleasure of watching it spin round and round. You pay for the pleasure of being warm in your home, having hot water, and maybe an electric cooker and other electrical appliances. Does *all* the energy you buy—whether it is electricity, gas or oil—get used for performing these useful functions? Have you ever sat fuming in a traffic jam? Would you say that *all* the energy bought at the filling station was being used to perform the useful function of getting you comfortably and conveniently home from work?

As you see from your own answers to these questions, such things as the design of houses and cities and transport systems, and the economic factors that encourage or discourage different designs, are likely to have a pronounced effect on the gap between end-use and functional energy.

* In terms of presently known technologies, there is no way of converting the energy in a lump of uranium or plutonium *directly* into any useful form of energy, unless we regard the kinetic energy of the fission fragments, neutrons and photons produced in a nuclear explosion as a 'useful' form of energy.

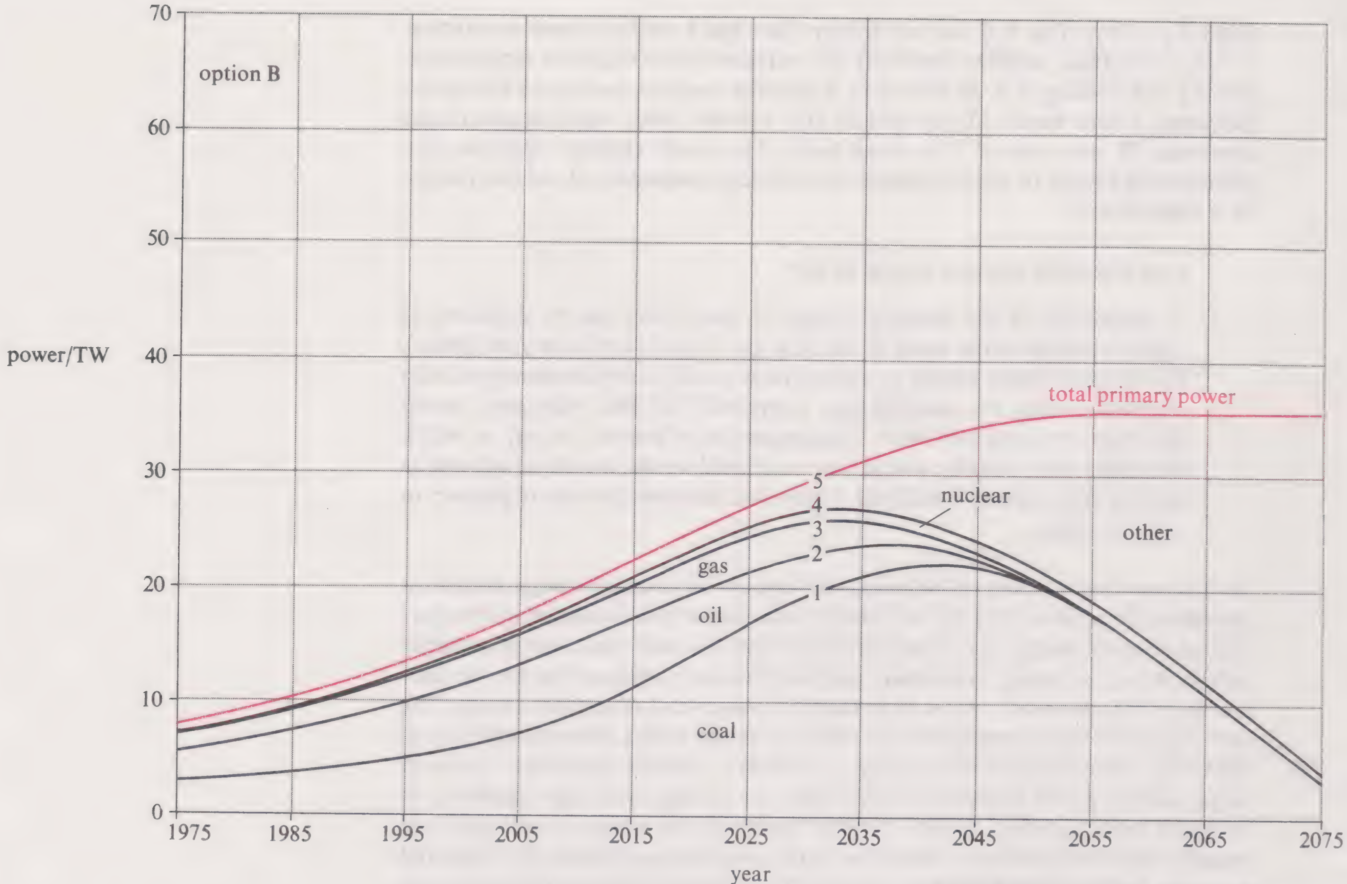


FIGURE 19 An alternative 'soft energy strategy' for meeting a primary power demand rising to a steady state level of 35 TW. The demand is met almost entirely (ultimately entirely) from energy income sources.

'hard' energy strategy/technology
'soft' energy strategy/technology

This strategy—of using energy systems that will allow the functional energy to rise to the required level to meet human needs without a commensurate rise in primary energy—is illustrated in Figure 19, which you should compare and contrast with Figure 16.

Figure 16 is an example of a '*hard energy strategy*' and Figure 19 is an example of a '*soft energy strategy*'. In the latter, energy capital sources are eventually replaced almost entirely by energy income sources, nuclear power is restricted to a maximum of 4–5 per cent of the total* in the second quarter of next century, and is reduced to a much smaller proportion thereafter, with fission power being replaced entirely by fusion power.

In the soft energy strategy (Figure 19), as in the hard energy strategy (Figure 16), coal provides the main interim source of power as oil and natural gas are phased out of the energy conversion scene. (Residual reserves would be conserved as feedstocks for essential chemical products.) However, the total energy converted from coal (which is equal to the area under the coal curve) is appreciably less in the soft energy strategy than in the hard energy strategy.

The essential features of such a soft energy strategy are that it depends on energy income instead of energy capital, it incorporates diversification and decentralization, with central electricity generation reduced to a minimum and, by better matching of end-use energy to function and better design of the context within which the two are matched, it maximizes the proportion of functional to end-use energy. Above all, it reduces considerably the environmental hazards characteristic of hard energy strategies.

You should now be able to distinguish some of the essential features of 'hard' and 'soft' energy strategies and technologies. Here is an SAQ to test this.

> **SAQ 11** Table 7 shows the pattern of primary energy conversion in ten hypothetical countries at some time in the mid-twenty-first century. The figures are the percentages of the total primary energy from each of the seven sources.

* This, nevertheless, represents between ten and fifteen times the installed nuclear-electrical capacity in 1975 of some 100 GW and five to seven times the installed capacity planned for 1980.

TABLE 7

Country	Percentage of primary energy from:						
	coal	oil	gas	nuclear	hydro-electric	solar	geo-thermal
A	40	31	15	10	4	0	0
B	25	5	4	6	5	45	10
C	0	0	0	96	2	2	0
D	30	12	10	3	4	37	4
E	0	0	0	0	7	85	8
F	26	6	4	60	3	0	1
G	5	0	0	2	3	75	15
H	20	15	10	35	5	5	10
I	20	10	5	20	2	40	3
J	10	6	4	4	6	65	5

(a) Which of the countries A–J would you say are adopting, essentially:

(i) a hard energy strategy,
(ii) a soft energy strategy,
(iii) an intermediate strategy?

(b) Of the countries A, C and F, in which would you expect to find the highest ratio of primary to end-use energy, and in which the lowest?

6 Conclusions

It would be absurd to try to draw hard-and-fast conclusions from the limited amount of evidence and analysis we have been able to compress into a single Course Unit. But we can at least draw your attention to a list of questions and points to think about.

1 The size of the problem humanity faces depends very much on the factor by which the *global* rate of primary energy conversion will increase over the next century. The estimates illustrated in Figures 3 and 16 suggested something like a ten-fold increase. Even with the possibility, illustrated in Figure 19, that alternative 'soft' energy technologies might reduce primary energy by half without decreasing end-use energy, there would still be a five-fold increase in primary energy and there would still be a major problem. But how confident can we be that such estimates are realistic? A recent study by the International Institute for Environment and Development* showed that even if the GDP of the U.K. trebles or doubles over the next 50 years, primary energy demand could be kept constant from now on or be reduced by 20 to 25 per cent. It is significant (and confirms the arguments of Section 5) that this study assumed a substantial *increase* in end-use and functional energy over the same period. The study also confirms one of the assumptions we made in deriving Figures 3 and 16, namely that zero growth in primary power may be achievable by the end of the first quarter of next century *in the industrially developed countries.* The big unknown remains the at-present less developed countries, and what happens there will affect the *global* outcome much more than what happens in the developed countries.

A recent report to the Club of Rome by an international working group chaired by Dennis Gabor and Umberto Colombo** concludes that:

> While energy saving is a must for industralized societies, less developed countries urgently need to increase their energy use in order to accelerate their process of development and to overcome the social and economic gap with respect to industrialized countries.

* G. Leach *et al.* (1979) *A Low Energy Strategy for the United Kingdom.* Science Reviews and the International Institute for Environment and Development.

** *Beyond the Age of Waste.* A report to the Club of Rome. Pergamon, 1978. This is one of the recommended further reading books (see Appendix 1).

A five- to ten-fold increase in the rate of primary energy conversion within the next 100 years thus seems to be not at all unrealistic.

2 If primary energy demand does, indeed, increase in the manner illustrated in Figure 16, is the method of meeting it, also shown in Figure 16, economically viable and environmentally acceptable?

3 If your answer to Question 2 is *no*, then you should ask yourself some question about the feasibility of the alternative option illustrated in Figure 19. Note that there are two basic differences between Option A (Figure 16) and Option B (Figure 19). In Option B, steady state primary power is about half what it is in Option A (but there is no reduction in end-use power—compare Figures 17 and 18). And, in Option B, energy *capital* sources (fossil and nuclear) are replaced by energy *income* sources (solar and geothermal).

But is this massive technological change-over feasible?

Look at Figure 19. By about 2040—barely 60 years from now—the primary power from 'other sources' would need to be about the same as the primary power from all sources *today*. How is this rapid rate of development of a range of solar and geothermal energy technologies to be achieved? They may well be technologically much simpler, less capital intensive, more labour intensive, more dispersed and more efficient than the technologies they would have to replace, but does it seem likely to you that such a development will be achievable without the diversion of very substantial research and development effort, followed by massive financial investment in these new technologies?

4 This brings us up against some major political questions:

(a) At present, about 40 per cent of the world's best qualified scientists and engineers are working directly on military research and development, on which the annual expenditure in the mid-1970s was about 30 billion dollars. Do you think it likely that research and development of new energy technologies, on the scale and at the rate implied by Option B, will actually be done while the arms race continues at the present level?

(b) The pattern of expenditure on energy research will need to change drastically if anything like Option B is to be achievable. In the United States, for example, in the years 1972–1974, an average of $500 million a year was spent on energy research and development, but of this, 84 per cent was on nuclear fission, 13 per cent on nuclear fusion, less than 3 per cent on solar energy and less than 1 per cent on geothermal energy. This was despite the fact that in 1972 extremely positive reports were issued by the National Science Foundation on both geothermal and solar energy.

By 1977 the pattern of government expenditure on energy research and development in the U.S.A. had changed significantly, as Figure 20 shows. The percentage devoted to nuclear fission had dropped to 47 per cent, and that on energy income sources had increased to 11 per cent. The comparison between the U.S.A., the U.K. and the ensemble of 17 member countries of the International Energy Agency* is interesting in several ways. It does confirm, however, that capital energy sources, particularly nuclear, are still getting most of the research and development effort.

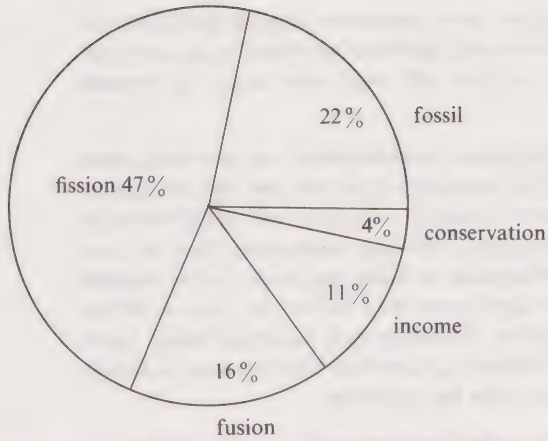
There are large vested interests in existing energy technologies and correspondingly powerful lobbies which influence government energy policies in many countries. There are also built-in inertias and self-perpetuating mechanisms in the high-technology industries concerned, as well as fears of redundancy among the people who work in them, fears which may be unfounded but are none the less real.

How are these political obstacles to be overcome? Is it likely that they will be overcome *in time*?

* Austria, Belgium, Canada, Denmark, Federal Republic of Germany, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States. The figures from which Figure 18 is drawn are from the 1977 *OECD Review*.

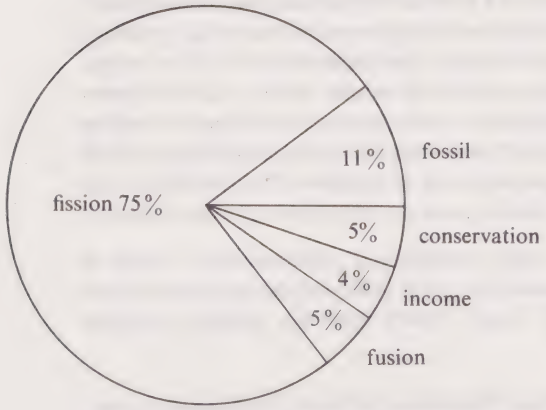
(a)

U.S.A. ($2 020 million)



(b)

U.K. ($236 million)



(c)

17 members
of I.E.A.
($3 830 million)

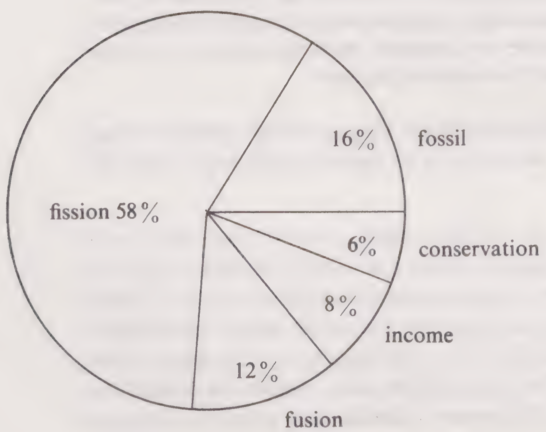


FIGURE 20 Government expenditure on energy research and development in 1977: (a) U.S.A., (b) U.K., (c) 17 members of the International Energy Agency.

5 The inherent time-lag in new technological development—even given the political will to achieve it—is another problem. The Club of Rome, in another of its conclusions on energy, poses this problem clearly:

> In attempting to develop new or improved energy sources of proven feasibility, we must realize that: (i) research and development on alternative energy sources is often very complex and success will depend on the effort deployed in each particular case; (ii) research and development has a long lag time (on the average 1–2 decades), and (iii) the widespread diffusion of new technologies generally takes even longer. The long lead-time of research must be taken into account in order to avoid the danger of unwarranted short term expectations.

6 There is another process with an inherently long time-lag between cause and consequence—the process of climatic change. Energy policies being implemented now *could* have serious effects on the climate decades hence. Changes in energy policies will take decades to carry out. Yet the science of climatology is at such an early stage of development that it is quite incapable of giving us unequivocal answers to urgent and important questions about the effects of various present and possible future energy policies on regional and global climate. This is not because the climatologists are incompetent. It is simply that the resources devoted to climatological research have been and are woefully inadequate.

The systems we are concerned with here have enormous inertias and slow response times. Not only will changes in energy policies take decades to carry out, but the climatic effects of present policies will take even longer to become apparent.

7 Then there is the question of international collaboration. As you study these global problems, you will constantly be reminded of the fact that they are *global*. Massive developments of nuclear power, coupled with wholesale proliferation of nuclear technology, could have consequences affecting many more than the contracting parties. The large-scale development of solar sea power in the tropical oceans might unbalance the climate and cause crop failures in Asia or Africa. Increasing combustion of fossil fuels by the energy-rich countries could, again through climatic effects, impoverish further the countries that are poor in energy and in everything else too. And so on—the list is endless.

You have seen in earlier Units of this Course how human life has evolved on this evolving planet, how the human species is a product of the planetary environment. In this Unit we have shown that the planetary environment is becoming a product of human activity, and the question of whether that environment will be propitious for or hostile to human survival cannot be settled within national boundaries. Indeed, the very scale and complexity of these global problems are such as to require *international collaboration*, both to create the conditions without which there is no hope of a solution being found, and to combine the intellectual and material resources of the nations in finding and carrying through that solution.

What, then, are the prospects of such international collaboration? Could it develop from the existing political machinery, or is some radical departure necessary? The authors of the Club of Rome report find the present situation discouraging:

> International organizations, with their difficulties of obtaining the consensus of nations at widely different stages of development, with contrasting environments, traditions and interests, are in a very unfavourable position to provide a world perspective or offer alternative models for world development. What is needed is a creative answer, that is, a solution departing from current practice.

If 'creative answers' are needed to these questions, then a crucial question must be: who is to supply these answers, and who is to decide about what must be done?

8 This brings us to the final point in our list, which concerns you, both as a science student and as a citizen. It concerns *power*, not in the scientific sense, but in the political sense. We do not refer to the comparatively trivial matter of what political parties are in power in particular countries, but to the more fundamental question of who has the power to decide what will happen to humanity in the coming decades. We think it should be you, and the many hundreds of millions like you who, together, have the potential power to decide that what does happen will be in the interests of humanity.

The task is enormous, and the contribution any one of us can make is minute. It is easy to be discouraged by this. Even to begin, one has to be informed, and that is not achieved without effort. But there is no other way.

We said in the Introduction that the Unit would be concerned with a set of interconnected problems: of population and poverty, power and pollution; and of peace, for world peace will assuredly be threatened if these problems are left unsolved, or if dangerous and unstable 'solutions' are pursued. Moreover, the moral and material resources needed for solving these problems are unlikely to be available in a world burdened by a crippling arms race. To the five problems listed in the Introduction, we have now added a sixth, that of the *power* to decide.

We hope that the scientific approach you have learned in this Foundation Course—and which you have been applying to some global problems in this final Unit—will enable you to use your rights, your power and your responsibility as a scientifically educated person to make your own, personal contribution to solving this problem of survival.

Objectives

This is the last Unit of this Course, and one of its Aims has been to show that the basic scientific concepts and methods you have learned in the preceding Units can be usefully applied to analyse a set of global problems affecting the human environment and possibly the survival of humanity. In the process of doing so, the Unit aims to reinforce your understanding of these basic concepts and your confidence in your ability to apply scientific methods of analysis to problems of this kind.

So some of the terms, concepts and processes listed in Objective 1 below were, in fact, introduced in earlier Units and some in this Unit.

Objective 1 You should be able to explain simply and to recognize essentially correct or incorrect explanations or uses of the following terms:

stored energy; unbinding energy; fuel; energy conversion; energy conversion path; heat energy; power; primary, end-use and functional energy; energy capital and income; renewable and non-renewable energy; cumulative energy demand curve; fossil fuel; nuclear fuel; burner and breeder reactors; conversion ratio; fast breeder reactor; fission products; plutonium; direct and indirect solar energy; 'active' and 'passive' direct solar energy technologies; photoelectric conversion of solar energy; a 'solar tower'; thermoelectrical, photosynthetic, hydroelectrical, wind, wave and ocean thermal energy; tidal energy; hydrothermal and hot dry rock sources of geothermal energy; radioactivity of fission products; substantial climatic change; environmental heat; general circulation model: aerosol; the greenhouse effect; diversion of plutonium; proliferation of nuclear weapons; toxic effects of plutonium; 'hard' and 'soft' energy paths and technologies.

A further Aim of this Unit has been to make you aware of the scale, complexity and interrelatedness of a set of global problems, of the seriousness of their implications and of the urgent need to find solutions to them; and to show you that these problems are not just scientific, but have important technological, economic and political aspects.

The following Objectives relate to this Aim:

Objective 2 You should be able to explain simply, and you should be able to recognize essentially correct or incorrect explanations of, or statements about, the following:

(a) What degree of correlation there is between per capita power conversion and per capita GDP, and why such a degree of correlation is to be expected. (SAQ 1)

(b) The current proportion of primary energy that comes from energy capital sources; the capacity of energy capital sources to meet specific energy demands; the potential contribution of energy income sources to possible future energy demands. (SAQ 4)

(c) What the specific environmental dangers are that would accompany a large-scale growth in nuclear energy and, in particular: why the environmental hazards of nuclear energy are *qualitatively* different from those of other industries, why plutonium is a particularly dangerous substance, what are some of the more obvious containment hazards of the nuclear fuel cycle, what are the special hazards of 'diversion' of plutonium, and why large-scale development of nuclear energy may cause further proliferation of nuclear weapons. (SAQ 10)

(d) The essential differences between 'hard' and 'soft' energy strategies and technologies. (SAQ 11)

One of the problems to which we have directed your attention in this Unit is that of the climatic effects that may be caused by the combustion of fossil fuels and by the release of stored energy from *any* fuels. These were discussed in Section 4.2.

Objective 3 From your study of this part of the Unit, you should be able to explain simply and to recognize essentially correct or incorrect explanations of, or statements about:

The reasons for concern about the possibility of climatic change; the reasons why there is uncertainty about future climatic change; the possible future climatic changes associated with fossil fuels, nuclear fuels and solar energy; the possible effects on climate of: waste heat, aerosols, atmospheric CO_2. (SAQs 5–9)

ITQ answers and comments

ITQ 1 (a) Reactions (1) and (2) are exothermic because more energy is needed to break the bonds between the atoms in the product molecules (CO_2, H_2O) than between the atoms in the reactant molecules (O_2, CH_4). In other words the sum of the products' *bond dissociation energies* is greater than the sum of reactants' bond dissociation energies.

Reactions (3) and (4) are exothermic because more energy is needed to break up the product nuclei ($^{95}_{39}Y$, $^{139}_{53}I$, $^{3}_{2}He$) into protons and neutrons than is needed to break up the initial nuclei ($^{235}_{92}U$, $^{2}_{1}H$) into protons and neutrons. In other words, the *unbinding energies* of the product nuclei are greater than the unbinding energies of the initial nuclei.

Notice the very close similarity between the two explanations and between the concepts of bond dissociation energy and (nuclear) unbinding energy.

(b) From reaction (3), the energy released per $^{235}_{92}U$ nucleus is 200 MeV or $200 \times 1.6 \times 10^{-13}$ J.

The energy released per gram of $^{235}_{92}U$ is, therefore:

$$(\text{energy per nucleus}) \times (\text{number of nuclei per gram})$$

$$= (200 \times 1.6 \times 10^{-13})\ \text{J} \times (6 \times 10^{23}/235)\text{g}^{-1}$$

$$\approx 8.2 \times 10^{10}\ \text{J g}^{-1}$$

Similarly, from reaction (4), the energy released per $^{2}_{1}H$ nucleus is 1.7 MeV (there are *two* deuterium nuclei, remember) or $1.7 \times 1.6 \times 10^{-13}$ J, and the energy released per gram of $^{2}_{1}H$ is, therefore:

$$(1.7 \times 1.6 \times 10^{-13})\ \text{J} \times (6 \times 10^{23}/2)\text{g}^{-1} \approx 8.2 \times 10^{10}\ \text{J g}^{-1}$$

(which is, coincidentally, almost exactly the same as for reaction (3)).

Note that the energy per gram from the nuclear reactions (3) or (4) is about 10^6 times as great as the energy per gram from the chemical reactions (1) or (2).

The difference is due to the fact that the strong force binding protons and neutrons together in a nucleus is about a million times stronger than the electrostatic force binding carbon, hydrogen and oxygen atoms together in a molecule.

ITQ 2 Plants use solar energy (photons) when they photosynthesize organic compounds from atmospheric carbon dioxide and water. In swamps, anaerobic bacteria cause biochemical changes that slowly transform the plant matter into peat and, as the peat deposits are buried beneath increasing thicknesses of younger sediments, they are compressed and heated, which gradually reduces the volume of the peat by expulsion of water and volatile organic compounds and increases the carbon content, until the peat is eventually transformed into coal.

Thus the energy 'stored' in coal is fossil *solar energy*. So is the energy 'stored' in natural gas and in petroleum (the two are usually closely associated). The process is in some ways similar to that of the formation of coal, though a bit more complicated. The original organic material in the case of petroleum and natural gas is marine plankton, the remains of which are deposited in fine-grained offshore muds, where slow decomposition by anaerobic bacteria turns the planktonic remains into an amorphous material. As the muds are buried and compressed by subsequent sediments, this amorphous material is converted to petroleum compounds by chemical and physical processes that are still not fully understood. Since the plankton themselves feed upon plant organisms (they are heterotrophes) that use solar energy to synthesize organic compounds, the stored energy in petroleum and natural gas is also fossil solar energy.

ITQ 3 The difference of 10.8 TW would be covered by the construction of 10.8×10^3 power stations of 1-GW (10^{-3} TW) capacity. The number of days in 25 years is $25 \times 365 = 9\,125$. So one would have to build $10.8/9.125 \approx 1.2$ such 1-GW power stations per day.

SAQ answers and comments

SAQ 1 C and E.

A is false because standard of living is not necessarily proportional to per capita GDP. Thus, even though per capita GDP and per capita power are *roughly* proportional to one another, it doesn't follow that standard of living is proportional to per capita power.

B is false; and C is true; there is at least a *rough* correlation.

D is false; there is *not* an *exact* correlation.

E is correct; as Table 2 indicates, the average DC has $5.0/0.44 \approx 11$ times the per capita power of the average LDC, and the average DC has $3.7/0.30 \approx 12$ times the per capita GDP of the average LDC. The same sort of rough correlation applies to individual pairs of rich and poor countries. For example, Canada has about 90 times the per capita GDP of Rwanda, and about 80 times the per capita power.

SAQ 2 (a) A and E.

Statements C and G are true, but are not relevant to the question whether wood is or is not an example of energy capital.

D is false. Not all fuels are examples of energy capital. Synthetic fuels, such as hydrogen or methanol, produced from organic waste material, are examples of energy *income*. So is wood, provided that the rate of usage is sufficiently low.

E is the relevant point: because wood can be replaced in a timescale of a century or so, which is comparable with the timescales we are considering here, it is reasonable to regard wood as income rather than capital. Of course, if you burn a whole forest in a week, you are treating it as energy capital, not energy income. If you burn a year's forest growth over a period much longer than a year, then you are using income, not capital.

F is clearly false, except in the trivial sense that a particular piece of wood, once burned, cannot be replaced.

(b) B, D, G.

Statements E and F are true, but they do not support the conclusion that geothermal energy is (on a timescale of hundreds or thousands of years) an energy income source.

Statement C is false; although heat *is* generated by crustal plate friction, the energy that is transferred in this process is the kinetic energy of plate motion, and this in turn was originally geothermal energy. The origin of geothermal energy is radioactivity.

SAQ 3 Only 1 and 3 are correct.

1 Remember that the conversion ratio is the number of fissile nuclei ($^{239}_{94}Pu$) produced divided by the number of fissile nuclei ($^{235}_{92}U$ or $^{239}_{94}Pu$) consumed. A reactor that produces more fissile material than it consumes is a breeder reactor.

2 No, *fast* breeder reactors are so called because they depend on the fission of $^{239}_{94}Pu$ (or $^{235}_{94}U$) by *fast* neutrons to produce a sufficient number of neutrons per fission reaction to achieve a conversion ratio greater than unity.

3 This is the correct definition of solar energy flux at the Earth's surface.

4 The term *passive* direct solar energy does not refer to whether or not the conversion process, if any, involves moving parts. It refers to modifications to the design of buildings that result in more effective use being made of the solar energy that is incident upon them.

SAQ 4 1, 5, 6, 7 and 11 are essentially correct.

1 In 1975, 97 per cent of the world's primary energy came from fossil fuels. These are non-renewable energy sources.

2 This is not correct. It is true that fossil fuels could not supply 60 TW yr of energy for more than about 100–150 years; $^{235}_{92}U$ could not meet this demand for even a decade. To meet such an energy demand from nuclear fission would be impossible unless burner reactors can be replaced by breeder reactors.

3 No, this is not true. Breeder reactors could, in principle, turn *all* the available uranium*, not just the fissile $^{235}_{92}U$ isotope, into potential fuel. This would extend the capacity of a given quantity of recoverable uranium to meet a given energy demand by a factor of about 140—but this is not the same as extending it indefinitely.

4 This is certainly false. Refer again to the discussion of indirect solar energy conversion (Section 3.2.2).

5 Essentially true. Hydrogen can be produced by dissociation of water or of organic materials (biomass wastes or specially cultivated 'energy crops'). Methane can be produced by fermentation of organic materials. Methanol can be produced from hydrogen (given a source of CO_2) or from organic materials. As fossil fuels are phased out of the primary energy conversion system, these synthetic fuels are likely to assume increasing importance.

6 True. But note that the former is 'capital' and the latter, in most circumstances, 'income'.

7 True. Refer back to Section 3.2.2.

8 No, this applies only to reactors in which fission is produced by *slow* neutrons. In these, the moderator is there to slow down the fast neutrons emitted when a nucleus undergoes fission. Fast breeder reactors contain no moderator material.

9 and 10 No, all nuclear (fission) reactors that use uranium as a fuel produce both $^{239}_{94}Pu$ and $^{240}_{94}Pu$.

11 True—see the comment at the end of the discussion of fission fuels in Section 3.2.3.

12 $^{6}_{3}Li$ may be an important fusion fuel, but *not* because energy can be extracted from the fusion of $^{6}_{3}Li$ and $^{2}_{1}H$. The energy comes from:

(a) the 'fission' of $^{6}_{3}Li$ when it captures a neutron:

$$^{6}_{3}Li + ^{1}_{0}n \longrightarrow ^{3}_{1}H + ^{4}_{2}He + 4.8\,\text{MeV} \qquad (3)$$

and (b) the fusion of the *tritium* produced by reaction (3) with deuterium:

$$^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6\,\text{MeV} \qquad (2)$$

SAQ 5 Here is a list of some of the disruptions we could think of. Don't worry if you didn't get all of ours. You may even have thought of some that we missed.

1 Heating bills would rise. (Winter bills dominate the annual totals.)

2 There would be a greater demand for end-use energy for space-heating.

3 Local authorities would need to buy a lot more snow-clearing equipment.

4 Farmers would have to house livestock in winter to a greater extent than at present.

5 The agricultural growing season would be shorter.

* Breeder reactors could also transform $^{232}_{90}Th$—which is not fissile, but is more abundant than uranium—into the fissile nucleus $^{233}_{92}U$. This would extend the capacity of nuclear energy by another large, but not infinite, factor.

(There would, of course, be compensations—for skiers and lovers of white Christmases! It is not that we couldn't *survive* or even enjoy greater winter snowfall, but that a considerable outlay of resources would be necessary to adapt to the change.)

SAQ 6 They all *might*! (Any event which anywhere adjusts the transfer of matter in the atmosphere, or the transfer of energy, may influence the climate of any region. But in many cases we can't be certain in what way or to what extent.)

SAQ 7 In the case of waste heat, the safe upper limit is less than 50 TW. In the case of aerosols, it is less than current rates i.e. less than about 0.3 Tkg yr^{-1}, and in the case of CO_2 it depends on the way the rate varies with time (see Figure 14, and the associated discussion). Thus (ignoring combined effects, about which little is known):

Scientist A Waste heat and aerosols are within safe limits. Siegenthaler and Oeschger predicted that in the long term the 'safe' CO_2 limit falls to about 3 Tkg yr^{-1}. On this basis, a rate of 2 Tkg yr^{-1} is safe in the long term.

Scientist B The waste heat limit is probably safe, but the aerosols limit, at about 1970s levels, may not be. According to Siegenthaler and Oeschger, the CO_2 rate is not safe in the long term.

Scientist C: These are not so much safe limits as levels at which some sort of substantial climatic change is likely.

Scientist D: !

SAQ 8 Methane, used as a fuel, burns to give CO_2. Hence, it would provide an abundant source of energy, but also an abundant source of atmospheric CO_2. It would, therefore, pose a climatic threat, unless some way were found of preventing the CO_2 being released into the atmosphere. In common with all ancient fuel reservoirs on Earth, this methane also poses a threat via the ultimate and inevitable transfer of its stored energy to the environment in the form of waste heat.

SAQ 9 Here is our answer:

strategy	reduction in climatic stress
A	5 (CO_2 is taken up as tree growth proceeds)
B	2,3,4 (therefore 5)
C	2,3,4 (therefore 5) (conservation results in less energy conversion from all sources, including fossil and nuclear fuels)
D	1
E	3,4 (but hazards peculiar to nuclear fuels do, of course, increase—see Section 4.3)

SAQ 10 *Answers:*

1 B	2 A	3 B	4 B	5 C
6 A	7 C	8 A	9 B	10 A
11 B	12 B	13 B	14 B	

Comments

1 Had the statement referred to *fission products*, it would have been essentially true. But the radioactive wastes from a nuclear reactor also contain the *actinides*, such as plutonium, which have much longer half-lives. Refer again to Figure 14.

2 Some, like plutonium, may be dangerous for other reasons as well, but that does not make the statement untrue.

3 This is not true. The safety of reactors is only one of the hazards of nuclear energy.

4 No, plutonium is radioactive because it is unstable and decays with the emission of α-particles.

5 This is debatable, and indeed still being debated between the experts. It is an interesting fact about the history of 'permissible doses' of radiation of all kinds that, as knowledge has increased, the

accepted limits have always been *reduced*. In any case, what constitutes a '*serious* risk' is still debatable.

6 This is true, because the consequences of taking the wrong decision could affect the lives of many unborn generations, as well as the lives of people at present living.

7 This is debatable. Though the safety record of the nuclear energy industry is indeed exemplary, nuclear energy has so far been developed only on a small scale and in a few countries. From one per cent of 7 TW to 100 per cent of 70 TW is a very big step!

8 By any standards 99 per cent is very efficient. But the remaining one per cent is a worry.

9 No, nuclear explosives can be made from reactor-grade plutonium, albeit with greater difficulty and less reliable performance than with weapon-grade plutonium.

10 This is true, because any such country will have ready access either to small quantities (less than 1% of the amounts it has to account for) of $^{239}_{94}Pu$ or to larger quantities of $^{239}_{94}Pu$ mixed with $^{240}_{94}Pu$.

11 This is wrong and it is most important to appreciate this fact. It is, of course, possible to make a nuclear weapon without having *any* nuclear power reactors—by separating $^{235}_{92}U$ from uranium and using that. It is also possible to build a reactor for the sole purpose of producing plutonium for nuclear weapons. But any country has a significant nuclear power capacity thereby also has the materials (and the technical skills) with which it can make nuclear weapons. Proliferation of nuclear power technology is therefore bound to make proliferation of nuclear weapons easier and hence more likely to occur.

12 Unfortunately this is not the case. True, fusion reactors would produce very much less radioactive waste products than fission reactors; but it is false to say they would not produce any.

13 Again, this is unfortunately not true. It would be relatively easy to breed $^{233}_{92}U$ from $^{232}_{90}Th$ in a fusion reactor by using the copious flux of neutrons from the fusion process.

14 This is completely false. 'Non-nuclear fuels' can only mean fossil fuels. As you saw in Section 4.2 the combustion of fossil fuels is potentially dangerous to the Earth's climate. It is also actually dangerous to health: estimates of deaths among the public in Britain from lung and bronchial troubles caused by the effluents of fossil fuel combustion range from a few hundreds to ten thousand per year. Additionally, the burning of coal in this country liberates about 100 tonnes of uranium (with all its radioactive daughters) into the air or into ash.

SAQ 11 *Answers:* (a) (i) Countries A, C, F and H; (ii) Countries E, G and J; (iii) Countries B, D and I.

(b) Country C would be expected to have the highest and Country A the lowest primary to end-use energy ratio.

Comments

(a) In countries A, C and F, 96 per cent of the primary energy is from nuclear and fossil fuels and only 4 per cent from energy income sources (hydroelectric, solar or geothermal). In country H, the proportions are 80 per cent capital and 20 per cent income. These countries are evidently adopting hard energy strategies. In countries E, G and J, most of the primary energy comes from renewable sources: 100 per cent in E, 93 per cent in G and 76 per cent in H. To varying degrees, these countries are evidently adopting soft energy strategies. Countries B, D and I are clearly somewhere in between: the capital contribution to B is 40 per cent and to D and I 55 per cent. Note, however, the different proportions of fossil and nuclear energy in D and I.

(b) All three countries A, C and F get 96 per cent of their primary energy from fossil and nuclear fuels. But note that in Country C, *all* of the 96 per cent comes from nuclear fuel, whereas in Country A only 10 of the 96 per cent does. Country F is in between the two, with 60 per cent from nuclear and 36 per cent from fossil fuel. Country C will necessarily be converting the highest proportion of its primary energy into electrical energy via heat energy, because there is no other way of converting nuclear energy into end-use energy. Thus Country C will be paying the highest 'heat engine penalty' and will therefore (other things being equal) be likely to have the highest primary to end-use energy ratio. For the same reasons, Country A would be likely to have the lowest ratio of the three.

Acknowledgements

Grateful acknowledgement is made to the following for permission to reproduce material in this Unit:

Text

D. Gabor *et al.* (1978) *Beyond the Age of Waste* (Club of Rome Report), Pergamon Press.

Figures

Figure 6 from article by R. S. Caputo in *Bulletin of Atomic Scientists*, May 1977; *Figure 7* from Lockheed Missiles and Space Co.; *Figure 9* from Applied Physics Laboratory, Johns Hopkins University.

Appendix 1 Recommended further reading

1 Amory B. Lovins (1977) *Soft Energy Paths*, Penguin, pp. 231.

2 Walter C. Patterson (1976) *Nuclear Power*, Penguin, pp. 304.

3 Gerald Foley and Ariane van Buren (eds) (1978) *Nuclear or Not?* Heinemann, pp. 208.

4 D. Gabor, U. Colombo, A. King, R. Galli (1978) *Beyond the Age of Waste*, A Report to the Club of Rome, Pergamon, pp. 220.

5 Amory B. Lovins (1975) *World Energy Strategies*, Ballinger, pp. 131.

The first four books should be readily available from most bookshops. The fifth can also be obtained from Friends of the Earth, 9 Poland Street, London, W.1. It has the merit of being both short and thought-provoking and we would recommend that you read it first. The Club of Rome report deals with materials and food, as well as energy, but the whole study is highly relevant to this Unit. *Nuclear or Not?* is an account of a Royal Institution forum in which leading pro-nuclear and anti-nuclear people presented their views and answered each others' arguments in front of an audience and television. We strongly recommend this book.

6 Bert Bolin (1975) *Energy and Climate*, Secretariat for Future Studies (Fack S-103, 10 Stockholm, Sweden), pp. 55.

This little booklet was produced as the first of a series of studies on Energy and Society funded by the Swedish Parliament. While stocks last you can probably get it for free by writing to the above address. It is directly relevant to the subject matter of Section 4.2 of this Unit.

7 Richard Wilson and William J. Jones (1974) *Energy, Ecology and the Environment*, Academic Press, pp. 353.

This is essentially a teaching text, complete with exercises and work-sheets. As it is a paperback and printed by camera-copy of typescript, it is not expensive and not as long as the number of pages might suggest. You will find in it much relevant information, careful explanation of scientific and technological points and many references.

8 Lon C. Ruedisli and Morris W. Firebaugh (eds) (1975) *Perspective on Energy*, Oxford University Press, pp. 527.

9 Oak Ridge Associated Universities, *Future Strategies for Energy Development*, pp. 297.

References 8 and 9 are each collections of separate papers by experts, and there is consequently quite a bit of variation in technical level. You will need to read selectively from these books and, since they are not cheap, these would be better consulted in a library.

10 Stephen H. Schneider and Lynne E. Mesirow (1977) *The Genesis Strategy—Climate and Global Survival*, Plenum Press, pp. 419.

This book, as its name suggests, is about the impact of climate on society (and vice versa). It is written by one of the world's leading climatologists. The late Margaret Mead commented on it: 'This brilliant book by a young, concerned scientist is just what the world needs . . . relevant, timely, essential for decision making. Solid, concerned common sense, buttressed with facts—but not too many for the layman to digest as a preparation for action.' We would agree with this view. Its price may deter you from buying it—but you might try to persuade somebody to give it to you as a present. Any good library should have it, though.

Appendix 2 Conclusions and recommendations on energy

(An extract from Chapter 2 of the Club of Rome report, *Beyond the Age of Waste*.)

The report was prepared by a working party of thirty-six experts from thirteen different countries, under the chairmanship of Dennis Gabor (U.K.) and Umberto Colombo (Italy).

The concluding paragraphs in the Chapter on Energy make very interesting reading as a postscript to this Unit. The book became available during the late stages of writing Unit 32. Beyond inserting three short quotations from it into the concluding section of the Main Text, we made no changes as a result of this authoritative study. Indeed, as you can see for yourself, many of the conclusions drawn by the Club of Rome working party are the same as our own. Our only comments on their conclusions might be that perhaps the climatic hazards of fossil fuel combustion have not received enough attention, and that the potential importance of ocean thermal energy conversion may have been underestimated.

We might also add that the thirteenth, and last, conclusion of the working party states one of the main reasons why we decided to include a Unit on this topic in our Science Foundation Course. Here are the concluding paragraphs of the report:

'*Conclusions and recommendations on energy*

1 The analysis of the present energy situation and prospects leads to the conclusion that the first and foremost effort in developed countries, which today consume 85% of the world energy demand against 30% of the world population, must be toward energy saving. Until recently, the relatively low cost of energy from hydrocarbons encouraged, beyond any reasonable limit, the building up of a general production and consumption pattern not constrained by problems of energy supply and cost and, therefore, inherently energy wasteful. At the same time, the availability of low-cost energy did not provide sufficient incentives for carrying out an intense research and development effort on energy.

2 In the light of the present awareness of the value of energy supply, it is clear that the economies of industrial societies must become more responsible and careful in the use of energy. Another reason for prudence in using energy is the environmental impact involved at all stages of the energy system—from raw material extraction to final use. In particular, it must be noted that adverse effects are not always immediate, but may only become apparent in the medium or long term. Especially important is the problem of the outer limits of energy use for maintaining an acceptable climate. Although the energy dissipated by human activities was once negligible with respect to that from natural phenomena, in some regions man-made energy now reaches a level comparable to incident solar radiation. The resulting hazards must be evaluated and possible long-term climatic and ecological effects of increased energy dissipation must be studied. Even though we cannot yet fix an exact outer limit, it is certainly not very high, and our long-range objective must be a society with an energy increase rate near to zero. The achievement of this long-range goal naturally requires the development of energy-saving technologies and of low-energy-intensive products and production systems. But another important factor is the efficient management of wastes in order both to exploit them as energy and raw material source, and to reduce environmental pollution.

3 While energy saving is a must for industrialized societies, less developed countries urgently need to increase their energy use in order to accelerate their process of development and to overcome the social and economic gap with respect to industrialized countries. High priority must therefore be given to providing these countries an increasing energy supply in order to satisfy their social and economic needs. This does not mean that their development necessarily implies a large waste of energy or a pattern leaning on high-energy-intensive activities.

4 Obviously the achievement of this aim depends on the social and economic situation in each developing country (especially in terms of capital availability and concentration of capital) as well as on their technological skill. For them to follow patterns of energy growth similar to those of industrialized countries would in fact involve an unbearable drainage of resources and would jeopardize a

balanced economic development. What appears to be the most appropriate solution for the Third World's nations is the adoption of a low capital- and low technology-intensive energy-development pattern, based whenever possible on the use of even minor domestic sources. This may well coincide with the need for these countries to develop efficient labour-intensive industries where a growing population means a relatively still greater work force.

This type of solution seems to be the best adapted to the social and economic situation of the developing countries, especially considering the importance of their rural areas. In addition, the development of energy along these lines can provide industrialized countries with useful long-term indications.

5 The present world energy situation is therefore confronted on one side with the need of saving energy in advanced societies and on the other with that of making more energy rapidly available to the developing countries, without undue dependence on capital-intensive technologies, which their economies would be unable to support.

6 The analysis of the prospects of the different energy sources in relation to the above-discussed problems leads to the following conclusions:

(i) Due to their flexibility and lower capital intensiveness in comparison with nuclear power, *oil and natural gas*, while playing a decreasing though fundamental role in industrialized countries, will represent in the next few decades the most appropriate main energy source for the developing countries.

(ii) Among fossil fuels, *coal* is the one with the largest reserves and, therefore, deserves special attention. Its utilization in industrialized countries involves, however, a large-scale development of gasification and liquefaction processes, allowing it to be employed as a substitute for hydrocarbons. For developing nations a massive utilization of coal is basically connected to local availability.

(iii) The spreading of the exploitation of non-traditional fossil fuels such as *tar sands and oil shales* depends on the development of economically sound technologies for the processing of raw materials and the production of hydrocarbons. The exploitation of these resources is, however, limited to those areas of the world where large deposits exist.

(iv) In developing countries rationally used *firewood*, a renewable carbonaceous fuel, must remain a useful substitute for coal, although lower in energy content. In fact it must be remembered that, like other organic fuels (e.g. cowdung), firewood has traditionally represented one of the main energy sources in the Third World's village economies.

(v) *Organic solid wastes* represent an energy source deserving special attention even in developed countries because it is renewable, grows proportionately to consumption, and its exploitation meets the requirement of eliminating pollution. This source can be exploited at different levels and with various systems according to a society's organization and technological development.

(vi) The potential of *hydroelectric* power is almost fully exploited in most developed countries, whereas in certain areas of the developing world it is substantially under-exploited and is large compared with local energy demand. In such regions therefore the role of this source can be highly significant.

(vii) The *potential of geothermal* energy is rather great for conventional sources of steam and hot water; for the long term there is the prospect of exploiting the heat stored in hot rocks and, ultimately, the heat of the earth's mantle.

(viii) *Solar energy* presents interesting medium and long term prospects, but its large-scale exploitation for the production of power or hydrogen or other fuels still involves considerable technical problems. However, for local and limited applications such as space heating and agriculture, it already represents a viable solution and all efforts should be made to rapidly spread its use.

(ix) On a world level non-traditional minor sources—*tides, waves, winds, ocean currents, thermal gradients*—do not offer significant short and medium term prospects. However, in some specific cases, such as that of winds, their utilization can significantly contribute to meet the needs of less developed economies.

7 At present the only alternative energy source to fossil fuels which is both technically feasible and economically viable is *nuclear fission*. However, it must be

pointed out that this kind of energy, besides being highly capital-intensive, involves serious safety and security problems with related environmental effects. Furthermore, in contrast with almost any other source, nuclear fission poses peculiar problems due to the political and military implications of its widespread and indiscriminate diffusion. These problems would be amplified with the increase of plutonium inventory brought about by the development of fast breeder reactors, which are advocated because they minimize the consumption of uranium. *Nuclear fusion* could overcome some of these problems; but, besides being even more capital-intensive than fission, it is a solution that, even by the most optimistic estimates, could be available for widespread use only in the next century.

8 From the foregoing considerations it can be inferred that, in spite of its higher capital intensiveness and other already mentioned drawbacks, a further development of nuclear fission energy today represents an unavoidable choice for the industrialized countries. But not even for these nations can it be considered as a preferential option to meet long term energy requirements. In fact, in addition to the above mentioned problems, extensive nuclear development requires the centralized management and regulation of a so rigid and complex macrosystem that it is doubtful whether it can be successfully kept under control.

9 From this standpoint nuclear energy emphasizes the already existing trend in the industrialized countries towards rigid and centralized energy system, especially in the electric power field. If this trend were to be intensified the development of alternative energy sources—especially solar energy—would be hindered. An energy policy directed toward a balanced development of centralized and decentralized production would also favour that of alternative sources.

10 The development of nuclear energy is then to be regarded as a choice limited in time and space, to be utilized to fill the energy demand gap during the passage from today's oil era to a new one based on a wide spectrum of primary sources.

11 In attempting to develop new or improved energy sources of proven feasibility, we must realize that (i) research and development on alternative energy sources is often very complex and success will depend on the effort deployed in each particular case; (ii) research and development has a long lag time (on average 1–2 decades), and (iii) the widespread diffusion of new technologies generally takes even longer. The long lead-time of research must be taken into account in order to avoid the danger of unwarranted short term expectations.

12 While the debate on energy is presently focused mainly on the issue of primary energy sources, it must be pointed out that more emphasis needs to be placed on energy conversion, storage and transportation, which constitute, in terms of investments, technical involvement and environmental impact, a very significant part of the overall energy problem. Therefore, much attention should be paid to the problems related to the further expansion of present energy conversion, storage and transportation systems. Moreover, there is need of further study of new types of systems (such as magnetohydrodynamics, high-energy density batteries and hydrogen), with special reference to their potential impact on economy and society.

13 We believe that, given adequate resources and respecting the long lead times involved, science and technology could provide adequate solutions to the long term energy problems on a world-wide basis. In view of the vital role of energy in modern society and the long term implications of policy decisions, choices should not be made in a technocratic way. In making such momentous decisions it is important to involve public opinion in order to obtain general consensus when defining energy policies, including those related to actions in research and development. It is necessary to find institutional ways of achieving consensus by involving universities, research institutes, industry, services and representing public opinion groups in general, so as to obtain the maximum number of elements to assist in the decision making process.

Scientists and technologists have a definite social responsibility in this education process.'

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